where the oxygen concentration is below the secondary ion mass spectrometry (SIMS) detection limit (about 10^{18} cm^{-3}). Because the material quality is excellent within the volume occupied by the base–emitter spacer charge region, recombination events do not take place. Therefore, measurement of the base current yields a nearly ideal slope with applied base–emitter bias of about 60 mV/decade current.

Finally, the IBM authors state, "Clean ac measurements on a SiGe HBT had still not been achieved and served as the next milestone." On the contrary, the Stanford/HP team reported high-frequency measurements shortly after their initial results were announced [7], [8].

The Stanford/HP team accomplished an important set of first time achievements that should be acknowledged including the first SiGe bipolar device by chemical vapor deposition.

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Comments on "Inversion Charge Modeling"

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***Abstract*—In the above paper, an implicit relationship for the inversion charge density in the channel of MOS transistors is presented. As an application, the deduction of a compact MOS transistor model is outlined. This correspondence compares some results of the previously mentioned paper with previous relevant publications.**

***Index Terms*—Inversion charge density, MOS transistors.**

The above paper[1] presents an implicit relationship for the inversion charge density in the channel of the MOS transistor [(2) in Gummel and Singhal]. Using this charge density formula, a simple law for the drain current in terms of the charge densities at the ends of the channel is deduced [(5) in Gummel and Singhal]. The calculation of total channel charges is then outlined [(8)–(10) in Gummel and Singhal]. Finally, the authors claim that the charge relation presented by them can be a basis for advanced MOS models. Equations (2) and (5) from Gummel and Singhal are presented here for convenience

$$(q_m - 1) + \ln(q_m) = v_{\mathrm{sat}} - v_{ch} \quad [\mathrm{Eq.}(2)] \tag{1}$$

$$i = \frac{q_{ms}^2 - q_{md}^2}{2} + q_{ms} - q_{md} \quad [\mathrm{Eq.\ (5)}] \tag{2}$$

q_m is the channel charge density normalized with respect to $-C_{ox}V_t$, where C_{ox} is the oxide capacitance per unit area and V_t is the thermal voltage. q_{ms} and q_{md} are the inversion charge densities at the source and drain ends, respectively. i is the normalized drain current and v_{ch} is the channel voltage, which takes the values v_{sb} and v_{db} at source and drain. All potentials are bulk referenced and normalized to V_t.

Since the authors do not use the most commonly utilized notations and they do not reference some important closely related publications, we shall comment on some results of Gummel and Singhal and compare them with previous work.

1) v_{sat}, which has been defined in the paper under consideration as saturation voltage, has been called pinch-off voltage (V_P) by several other authors [1], [8], [9]. The notation v_{sat} may mislead the readers into assuming v_{sat} to be the saturation voltage of the output characteristics of the MOSFET. There are several definitions [1], [2] of saturation voltage in the technical literature. Some of them differ quantitatively but all of them have a common qualitative property, i.e., the inversion charge density at drain is much less than the inversion charge density at source. As a consequence, the saturation phenomenon implies a nonuniformity of the channel and the saturation voltage depends, in general, on the source potential. On the other hand, Gummel and Singhal define saturation voltage as the channel voltage such that the normalized inversion charge density equals one. Gummel and Singhal's definition of saturation does not fit a general MOSFET model. For instance, assume a transistor operating in weak inversion, i.e., the normalized charge density along the channel is less than one.

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According to the definition of Gummel and Singhal, the MOSFET would never enter saturation for weak inversion. Moreover, because Gummel and Singhal do not use any standard analytical expression for $v_{\rm sat}$ (i.e., V_P in some previous publications [1], [8], [9]) and do not give an explicit expression relating the saturation (pinch-off) voltage with the threshold voltage, comparison with previous results may not be obvious.

2) Expression (2) used by Gummel and Singhal, which is the most fundamental expression of the paper under analysis, has been used by several authors [4], [5], [11]. It was first presented as an empirical relationship in [4], [5], and demonstrated to be derived from physics in [11]. It has been named the Unified Charge Control Model (UCCM). Indeed, several authors have described the MOSFET characteristics through a unified expression for all operating regions [2]–[13].

3) Expression (5) used by Gummel and Singhal has been derived in several other papers [3], [4], [6], [9], [10], and books [1], [2], [12]. In fact, it can be deduced without using UCCM, assuming an incrementally linear relationship between surface potential and inversion charge density along the channel as carried out by Maher and Mead in [3], where the authors even considered the effect of velocity saturation in the drift term.

4) Once (5) has been derived, the calculation of charges and capacitances is straightforward. For details, see [6], [7], [9], [12]. Explicit expressions for the capacitance coefficients are given in [9], [10], [12], and [13].

5) Expression (12) in Gummel and Singhal introduces two new parameters into the UCCM formula. h_x is included to provide strong inversion with a better approximation while t_e is a parameter that accounts for drain-induced barrier lowering. To compare (12) in Gummel and Singhal with the analogous formula in [11]–[13], we will consider the derivative of the local inversion charge densities with respect to the channel voltage deduced from (12) and given in (5) in [11]. Using normalized variables as in Gummel and Singhal, (5) from [11] can be written as

$$\left(\frac{C_{ox}}{C_{ox}+C_b}+\frac{1}{q_m}\right)dq_m=-dv_{ch}\quad \text{[11, Eq. (5)]} \tag{3}$$

where C_b is the depletion capacitance per unit area and the other symbols are the same as in Gummel and Singhal. This equation corresponds to a small-signal model in which the inversion capacitance (proportional to the charge q_m) is connected in series with the parallel association of C_{ox} and C_b. The capacitive ratio $(C_{ox}+C_b)/C_{ox}$ is usually represented by n [1], being called the slope (or subthreshold) factor.

Taking the derivative of (12) in Gummel and Singhal

$$\left(h_x+\frac{t_e}{q_m}\right)dq_m=-dv_{ch} \tag{4}$$

it follows that if we consider $h_x = 1/n$, the only difference between the previous two equations is the term t_e, used in Gummel and Singhal to model the subthreshold slope of short-channel transistors. In fact, there are other ways to model the substhreshold regime in short-channel transistors using UCCM [5].

6) Concerning the final comment: "It is believed that this inversion relation can be a basis for advanced MOS models," it must be observed that this inversion relation has already been used as the basis of some advanced MOS models [4]–[7], [11]–[13].

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