Application of Electrical Effective Channel Length and External Resistance Measurement Techniques to a Submicrometer CMOS Process

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Abstract—Several new methods to extract the effective channel length (L_{eff}) and series resistance (R_{ext}) parameters for MOS devices have been proposed recently. This is a result of inaccuracies in standard techniques as device lengths are reduced to 1.0 μm and lower, especially with the introduction of lightly doped drain (LDD) transistor structures. In this study, several methods are applied to MOSFET's fabricated in a submicrometer CMOS process, and the limitations of the extraction routines are analyzed and compared. It is found that the limiting factors are the applicability of the V_t calculations and the precision of the I_{ds} measurements.

I. INTRODUCTION

IN the past few years, several techniques [1]–[3] have been presented that measure the effective channel length (L_{eff}) and external resistance (R_{ext}) of MOS transistors. They have been developed because of the inaccuracy involved in using standard methods as MOSFET channel dimensions are reduced to below 1.0 μm . Also, the use of lightly doped drain (LDD) structures has made measurement of the parasitic resistance more important for modeling transistor performance [4], [5]. An analysis of several electrical techniques using device simulation indicated that various physical factors influenced parameter extraction routines and suggested some modifications to correct these problems [6], [7]. In this study, various techniques are used to measure L_{eff} and R_{ext} for both conventional and LDD MOSFET's fabricated in a submicrometer CMOS process, and the limitations involved in their application are discussed.

II. EXTRACTION METHODS

For an MOS device operating in the linear region, the total dc resistance can be modeled as [8]

$$R_{ds} = V_{ds}/I_{ds} = A \times (L_{\text{eff}}) + R_{\text{ext}} \quad (1)$$

since

$$L_{\text{eff}} = L_m - dL \quad (2)$$

we can write

$$R_{ds} = A \times L_m + B \quad (3)$$

where

$$B = -A \times dL + R_{\text{ext}} \quad (4)$$

and

$$A = [\mu_{\text{eff}} \times C_{\text{ox}} \times W_{\text{eff}} \times (V_{gs} - V_t - 0.5 \times V_{ds})]^{-1} \quad (5)$$

L_m is the mask length of the device and dL is the reduction of the length from L_m due to poly undercut, source/drain diffusion, etc. All other symbols have their usual meanings. A plot of R_{ds} versus L_m can be fitted by standard linear regression algorithms [9] to find both the A (slope) and B (y-intercept) parameters. If a series of differing bias conditions is applied, a family of R_{ds} – L_m lines can be used to obtain a set of (A , B) points. Analyzing a plot of B versus A by regression can determine the values of dL (slope) and R_{ext} (y-intercept). A more complete treatment of the extraction method and its assumptions can be found in [8]. The most questionable assumption in the model is that dL and R_{ext} are constants for the range of biases used. It has been shown that this may not be the case, especially for LDD devices [5], [6]. For this reason, the use of small bias ranges for individual dL and R_{ext} calculations is preferable.

There are essentially two ways to vary the bias conditions to create this family of R_{ds} versus L_m lines:

- 1) fix V_{bs} and vary V_{gs} , as in [1] or
- 2) fix V_{gs} and vary V_{bs} , as in [4].

It was noted [1], [8] that if the devices used had differing V_t values, the proper method was to adjust V_{gs} so that $V_{gs} - V_t = V_{gst}$ was equal for all transistor lengths. This new method, termed the gate-drive (GD) technique, then varies V_{gst} to produce the data needed for parameter extraction. Fig. 1 shows the use of the GD method to obtain dL and R_{ext} for a conventional MOS device. In order to eliminate the geometry (or short-channel) effect associated with substrate bias methods, a substrate-bias gate-drive (SBGD) routine was developed [6], [7]. In this method, V_{gs} of the longest device remains constant for all substrate biases. Since V_t varies with V_{bs} , each set of R_{ds} – L_m data in the SBGD method is found from a particular (V_{gst} , V_{bs}) combination. Fig. 2(a) and (b) displays the application of the SBGD method.

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Fig. 1. Gate-drive (GD) method applied to conventional MOS device (a) to obtain A and B parameters and (b) to obtain dL , R_{ext} values.

Fig. 2. Substrate-bias gate-drive (SBGD) method applied to (a) obtain A and B parameters and (b) to obtain dL , R_{ext} values.

The determination of V_t for each transistor was also found to be critical, especially when using small gate drives [7]. A standard technique for obtaining V_t uses the linear region $I_{ds}-V_{gs}$ curve. At the point of maximum transconductance ($G_m = \Delta I_{ds}/\Delta V_{gs}$), the curve is linearly extrapolated to zero current. The gate voltage corresponding to this point is the threshold voltage. This method was shown to be sensitive to R_{ext} , although it was noted that a first-order resistance correction adjusted V_t to give satisfactory results [7]. The authors suggested that the use of a fixed-current method, where V_t is the gate voltage corresponding to a specified I_{ds} (normalized to unit W_m/L_m), was more consistent.

III. EXPERIMENTAL DETAILS

Both conventional and LDD devices with $L_m = 1.0, 1.5, 2.0, 3.0,$ and $10.0 \mu m$, and $W_m = 25.0 \mu m$ were used for the L_{eff} and R_{ext} measurements. These devices were built in a submicrometer CMOS process. Table I shows some processing details for the three NMOS device structures (CONV, LDD1, LDD2) fabricated. The p-channel transistors did not have LDD structures. Table II shows parametric data for $L_m = 0.6 \mu m$ devices made in this process. The linear region data for the techniques was taken using an HP4145 Semiconductor Parameter Analyzer controlled by an HP1000 computer. The biases applied (with opposite polarity for PMOS) were $V_{bs} = 0$ to

Fig. 3. (a) Comparison of different V_t techniques using SBGD method and conventional MOS devices. (b) Use of the corrected G_m technique for the SBGD method and conventional MOS devices.

TABLE I
PROCESSING INFORMATION FOR THE THREE DEVICE TYPES USED IN THIS STUDY

	CONV	LDD1	LDD2
T_{ox} (nm)	19	19	19
Spacer (μm)	None	0.1	0.15
N dose ($\#/cm^2$)	None	1×10^{13}	1×10^{13}
N energy (keV)	None	30	45
P dose ($\#/cm^2$)	None	None	None

TABLE II
n-CHANNEL AND p-CHANNEL PARAMETRIC DATA FOR ALL THREE MOS STRUCTURES FOR $L_m = 0.6 \mu m$

	CONV		LDD1		LDD2	
	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS
I_{dsat} (mA)	12.0	7.6	9.1	5.6	9.0	4.8
V_t (volts)	.442	-.63	.548	-.922	.494	-.943
G_m ($\mu A/V$)	198	82	171	69	172	62
SubVt slope (mV/decade)	97	104	94	122	94	112

$-5 V$; V_{gs} was 0 to 5 V in 50-mV increments; $V_{ds} = 50$ mV for all data points. The GD and SBGD methods were analyzed using both fixed-current ($I_{ds} = 0.2 \mu A \times W_m/L_m$) and maximum G_m techniques for determination of the threshold voltage. This resulted in four methods being compared:

- 1) GD using fixed-current V_t : GD(I_{ds})
- 2) SBGD using fixed-current V_t : SBGD(I_{ds})
- 3) GD using maximum slope V_t : GD(G_m)
- 4) SBGD using maximum slope V_t : SBGD(G_m)

Approximately ten sites per device type were tested to obtain the dL , R_{ext} parameters. The values shown in the figures and tables are the averages for all sites. It has been noted [8] that the selection of device lengths and applied biases can affect the results of the regression analyses. While small variations in dL and R_{ext} occurred if the selection of mask lengths and bias conditions was changed, the overall trends were not altered.

IV. RESULTS AND ANALYSIS

Fig. 3(a) shows the dL versus V_{gst} measurements for the CONV MOSFET's using the SBGD(I_{ds}) and SBGD(G_m) techniques. For $V_{gst} > 1$ V, the agreement is very good, but for smaller V_{gst} , the SBGD(I_{ds}) method indicates a slight increase in dL while SBGD(G_m) shows a small decrease. Fig. 4(a), a plot of R_{ext} versus V_{gst} for LDD1 transistors shows that the GD(I_{ds}) and GD(G_m) techniques follow the same pattern. In fact, this pattern emerged for both dL and R_{ext} for all three device types. The modulation of source/drain carrier concentrations by gate bias, which occurs in an LDD transistor [5], would cause dL and R_{ext} to increase for smaller V_{gst} . This suggests that the SBGD(G_m) and GD(G_m) methods predict incorrect trends at the lower V_{gst} values. The cause of this inconsistency is the V_t calculation since it is the only difference between these methods and the others used. It is not surprising that the fixed-current methods are more accurate at small V_{gst} values when you consider how the different V_t calculations fit the linear region model. The dL , R_{ext} extraction methods used assume that the intrinsic channel resistance/unit channel length (A parameter) is equal for all devices at a given bias (V_{gst} , V_{bs}) condition. Using a fixed-current V_t calculation requires the total resistance/unit mask length to be equal for all devices at $V_{gs} = V_t$, while the G_m ex-

Fig. 4. (a) Comparison of different V_t techniques using GD method and LDD1 devices. (b) Use of the corrected G_m technique for the GD method and LDD1 devices.

Fig. 5. Comparison of SBGD(I_{ds}) and GD(I_{ds}) methods using conventional MOS devices.

Fig. 6. Comparison of SBGD(I_{ds}) and GD(I_{ds}) methods using LDD1 devices.

trapolation only assumes this to be true at the point of maximum transconductance. The inclusion of biases near this gate voltage (typically $V_{gs} \sim V_t + 0.5$ V) requires using I_{ds} points that do not have equivalent intrinsic resistance/unit channel length values, and therefore the regression results are incorrect. Correcting G_m for the series resistance removes this source of error. Using the corrected V_t calculation proposed in [7], we see (Figs. 3(b), 4(b)) that equivalent dL and R_{ext} values will be found using either the fixed-current or corrected G_m calculations of V_t . For $V_{gst} < 0.5$ V, the fixed-current and corrected G_m methods also project nonphysical behavior, which implies

that the techniques violate the model assumptions at very low gate drives.

Figs. 5 and 6 plot dL versus V_{gst} data using the SBGD(I_{ds}) and GD(I_{ds}) methods for the CONV and LDD1 devices. On both plots, the GD technique indicates a larger change of dL and also depicts a sharp drop for $V_{gst} > 2$ V. Fig. 7 shows R_{ext} versus V_{gst} values for these two techniques using LDD2 data. Here the curves are in good agreement with each other although the GD(I_{ds}) data is not as smooth. Fig. 8 is a plot of the B versus A linear correlation coefficient [9] versus V_{gst} for the two methods and all three device structures. For $V_{gst} > 2.0$ V, the cor-

Fig. 7. Comparison of SBGD(I_{ds}) and GD(I_{ds}) methods using LDD2 devices.

Fig. 8. Correlation of second regression versus V_{gst} for all device types using SBGD and GD methods.

Fig. 9. Plot of B versus A parameters for $V_{gst} \sim 0.5$ V and conventional MOS devices.

relation coefficient for the GD(I_{ds}) method starts to decrease rapidly. Figs. 9 and 10 explain why. For $V_{gst} \approx 0.5$ V, the range of (A , B) values is very large (Fig. 9), but it is much smaller at $V_{gst} \approx 2.5$ V (Fig. 10), especially for the GD(I_{ds}) method. Deviations in R_{ds} measurements that cause slight inaccuracy in the calculated values for A and B can have a substantial impact on the slope (dL) at high V_{gst} . These inaccuracies cause the data to be less linear, resulting in a lower correlation coefficient. However, the extrapolation of this inaccurate slope to find the y-intercept (R_{ext}) is not large enough to significantly alter the R_{ext} value. Since the SBGD(I_{ds}) technique fits the B versus A regression over a slightly wider range of values at high gate drives, it is less affected by this influence. However, a limit of $V_{gst} \sim 3.5$ V appears to exist for SBGD(I_{ds}) methods.

The four methods were also applied to PMOS transistors fabricated in these processes. The trends at high and

Fig. 10. Plot of B versus A parameters for $V_{gst} \sim 2.5$ V and conventional MOS devices.

Fig. 11. Use of the SBGD (I_{ds}) method to find dL for p-channel devices.

Fig. 12. Use of the GD (I_{ds}) method to find R_{ext} for p-channel devices.

TABLE III
VALUES FOR dL (μm) VERSUS V_{gst} FOR ALL THREE PROCESSES USING THE SBGD (I_{ds}) TECHNIQUE

$ V_{gst} $	CONV		LDD1		LDD2	
	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS
0.5	.190	.413	.201	.331	.238	.279
1.0	.177	.384	.187	.311	.208	.226
1.5	.166	.374	.171	.294	.173	.198
2.0	.161	.372	.159	.280	.146	.184
2.5	.158	.375	.149	.272	.114	.175
3.0	.155	.370	.146	.267	.095	.164

TABLE IV
VALUES FOR R_{ext} (Ω) VERSUS V_{gst} FOR ALL THREE PROCESSES USING THE SBGD (I_{ds}) TECHNIQUE

$ V_{gst} $	CONV		LDD1		LDD2	
	NMOS	PMOS	NMOS	PMOS	NMOS	PMOS
0.5	112	361	126	377	157	390
1.0	94	294	108	314	136	320
1.5	83	237	95	275	121	276
2.0	76	209	87	251	111	246
2.5	72	198	81	234	103	221
3.0	68	190	78	218	98	204

low V_{gst} drives were very similar, except that the upper V_{gst} usable was ~ -4.0 versus 3.5 V for n-channel devices. This is due to the higher intrinsic channel resistance of the PMOS devices, so that R_{ds} variations are less significant. Figs. 11 and 12 are representative plots of dL and R_{ext} for the PMOS transistors. "LDD1" and "LDD2" refer to the process used to fabricate the devices, not the type of structure.

V. SUMMARY AND CONCLUSIONS

This study examined the practical application of four techniques used to measure L_{eff} and R_{ext} . Both conventional and two LDD structures fabricated in a submicrometer CMOS process were used. The results indicate that all the extraction methods are applicable to both n-channel and p-channel devices, although some are only valid over a small range of gate biases. Inconsistencies in applying V_t calculations to the extraction equations set a lower limit for V_{gst} of ~ 0.5 V, while the upper limit of 2.0 – 4.0 V arises due to imprecision in R_{ds} measurements influencing the double regression steps involved in the techniques. The SBGD (I_{ds}) method was applicable over a wider range of bias conditions than the other techniques analyzed and is easier to implement, which makes it the most suitable technique. Tables III and IV give dL and R_{ext} data for the SBGD (I_{ds}) method for all three processes and both NMOS and PMOS devices.

Unfortunately, it is difficult to independently verify the results of these measurements quantitatively. SEM techniques used on conventional device structures show good agreement with the electrical techniques [10], but are not easily applied to LDD transistors. Physical trends such as

source/drain modulation of LDD regions indicated by the calculations qualitatively match the expected device behavior. Device simulations [6], [7] also support the accuracy of the methods. This kind of evidence from such varied sources gives support to using the methods, but does not verify their application.

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