A Novel Method for Extracting the Metallurgical Channel Length of MOSFET's Using a Single Device

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***Abstract*—A new charge-pumping method with dc source/drain biases and specified gate waveforms is proposed to extract the metallurgical channel length of MOSFET's by using a single device. Using two charge-pumping currents of a single nMOSFET measured under different V_{GL} (V_{GH} for pMOSFET's), the metallurgical channel length can be easily extracted with an accuracy of 0.02 μm. It is shown that the proposed novel method is self-consistent with the results obtained by the charge-pumping current measured from multidevices under different gate pulse waveforms and bias conditions.**

I. INTRODUCTION

THE metallurgical channel length (L_{met}) is an important physical parameter for MOSFET characterization and modeling and is usually used to monitor lithography, etching and diffusion processes. Many efforts [1]–[5] have been made to determine the metallurgical channel length, based on the turn-on I–V characteristics of MOSFET's operated at low drain bias. The charge-pumping measurement technique is a reliable tool for MOS interface characterization [6]–[10], and the related experimental and analytical procedures are simple and fast. Recently, the charge-pumping current measurement has been applied to extract the metallurgical channel length of MOSFET's with very high accuracy (0.01 μm resolution) [9]. In this paper, a novel charge-pumping method using only one MOSFET device is proposed to determine the metallurgical channel length. It is shown that the accuracy of the new method is slightly worse than the multidevice method [9], however, the new method is simple and is feasible to deal with a large number of samples.

II. MODEL DERIVATIONS AND EXTRACTION METHOD

Using the effective area approach [9] and assuming the constant interface-trap density along the channel direction, the charge-pumping current can be expressed as

$$\frac{I_{cp}}{f} = Q_{sat}L_{cp}W \tag{1}$$

where L_{cp} is the length of the effective area, W is the channel width, and Q_{sat} is the recombined charges per cycle and can be approximately expressed as [7]

$$Q_{sat} \simeq q\int_{E_1}^{E_2} N_{it}(E)\,dE = q\overline{N_{it}}(E_2 - E_1) \tag{2}$$

with

$$E_1 = E_i + \frac{kT}{q}\ln(\sigma_{po}v_{th}n_i t_{emh}) \tag{3}$$

and

$$E_2 = E_i - \frac{kT}{q}\ln(\sigma_{no}v_{th}n_i t_{eme}) \tag{4}$$

where E_i is the intrinsic Fermi energy, k is the Boltzmann constant, T is the absolute temperature, σ_{p0} (σ_{n0}) is the hole (electron) capture-cross-section, v_{th} is the thermal velocity, n_i is the intrinsic carrier concentration, and t_{emh} (t_{eme}) is the nonsteady-state hole (electron) emission time, which is a function of rising/falling slopes of the gate-pulses (S_R/S_F) and substrate bias (V_{SUB}).

The setup and applied waveform are shown in Fig. 1. If we measure the charge-pumping current with the waveforms of the same S_R, S_F, and V_{SUB} but different V_{GL} or T_L, we can derive the charge-pumping currents related to the same Q_{sat} but different L_{cp}. Measuring the charge-pumping currents for two applied low gate voltages V_{GL1} and V_{GL2}, the metallurgical channel length can be derived from the following equation:

$$\frac{\Delta\frac{I_{cp}}{f}}{2(x_1 - x_2)} = \frac{\frac{I_{cp}}{f}(V_{GL1})}{L_{met} - 2x_1} = \frac{\frac{I_{cp}}{f}(V_{GL2})}{L_{met} - 2x_2} \tag{5}$$

where $\Delta(I_{cp}/f)$ is the difference of charge-pumping current per cycle; $x_1(x_2)$ is at the edge of the effective area near the source under V_{GL1} (V_{GL2}), as shown in Fig. 1 ($x = 0$ is located at the source junction). Note that $x_1(x_2)$ is located at the position where the surface hole concentration is p_c under $V_{GL1}(V_{GL2})$, and p_c is the critical surface hole concentration related to half-maximum of I_{cp}/f versus V_{GL} curves. The extraction method for p_c had been mentioned in [9] and p_c is 1.65×10^{15} cm^{-3} when $T_L = 1$ μs. From [10], we know that the product of p_c and T_L is a constant, therefore the edges of the effective area with respect to any V_{GL}, V_{SUB}, and T_L can be obtained by calculating the surface hole concentration of a MOSFET operated with V_{GL} and V_{SUB} using a 2-D numerical simulator.

Comparing with the multidevice method [9], the metallurgical channel length can be extracted from only two charge-pumping currents of a single device and can also be applied to

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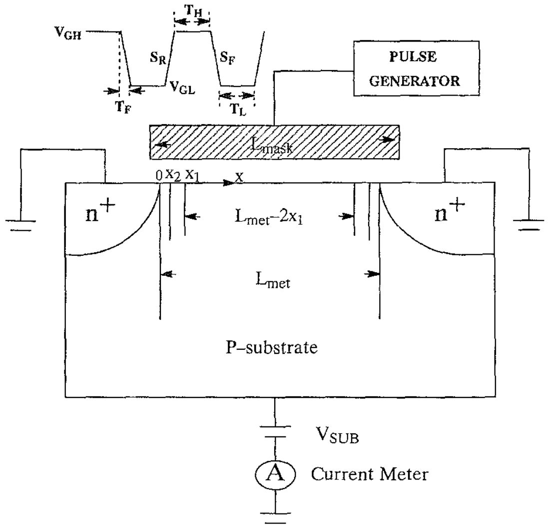


Fig. 1. The experimental setup and the applied gate pulse waveform for charge-pumping current measurement and a schematic device cross-section showing the definition of L_{met}, L_{mask}, x_1, and x_2.

interface-trap uniformity analysis. However, there are several points to be noted while using (5). 1) The V_{GL}, V_{SUB}, and T_L used for charge-pumping current measurement should be chosen to keep x_1 and x_2 located in the channel region with constant interface-trap density, because the interface-trap density is larger near the source/drain region and decreases to a constant value in the center of the channel. In general, x_1 and x_2 should be kept away from the junction more than 0.02 μm, otherwise, the L_{met} will be underestimated. 2) $\Delta(I_{cp}/f)$ in (5) should be derived from two charge-pumping currents measured under the same S_R, S_F, and V_{SUB}, otherwise, further error will be induced. The error can be approximated as

$$L_{error} = \frac{L_{met} - 2x_1}{1 + \frac{x_1 - x_2}{L_{met} - 2x_1} \frac{E_2 - E_1}{\Delta E}} \tag{6}$$

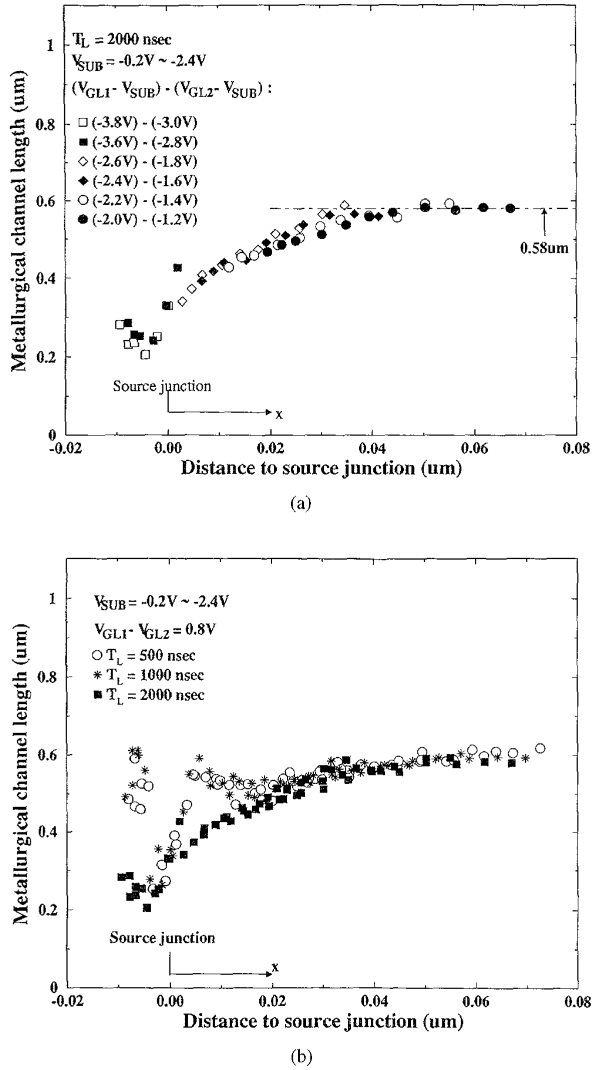
where ΔE is the difference of the effective interface-trap range in the bandgap for different S_R, S_F, and V_{SUB}. If S_R, S_F, and V_{SUB} are unchanged, ΔE approaches zero and the error can be ignored. 3) To reduce the error, x_1 and x_2 should not be too close. For example, the charge-pumping current error induced by measurement is I_{error}, then the induced error in the extracted L_{met} using (5) can be expressed as

$$L_{error} = \frac{L_{met} - 2x_1}{1 + \frac{x_1 - x_2}{L_{met} - 2x_1} \frac{I_{cp}(V_{GL1})}{I_{error}}}. \tag{7}$$

It is clear that $(x_1 - x_2)$ becomes small, L_{error} will become serious. Because the interface-trap density of an unstressed device is low (around 1×10^{10} cm$^{-2} \cdot$eV^{-1}), so the measured charge-pumping current is small, and I_{error} becomes the major error source of this method.

III. Experimental Results

The experimental transistor used to demonstrate the novel method proposed in this paper is an n-channel MOSFET with



(a)

(b)

Fig. 2. The metallurgical channel length derived from (a) different $(V_{GL} - V_{SUB})$, and (b) different T_L. Note that the data point along the x-direction is calculated by defining $x = (x_1 + x_2)/2$.

the mask channel length (L_{mask}) of 0.8 μm and the channel width of 100 μm. The $I_{cp}(V_{GL}, V_{SUB})/f$ data are measured with V_{GL} varying from $-3.8 + V_{SUB}$ to $-1.2 + V_{SUB}$ V and V_{SUB} varying from -0.2 to -2.4 V. T_L varies from 0.5 to 2 μs and both $S_R(0)$ and $S_F(0)$ are 2×10^6 V/s. As shown in Fig. 2(a), the saturation value in the channel is about 0.58 μm and $\Delta L = 0.22$ μm ($\Delta L = L_{mask} - L_{met}$) is equal to the value derived from the multidevice method [5]. As mentioned in the previous section, when x_1 and x_2 are near the junction, the interface-trap density is higher than that in the middle of the channel and the extracted L_{met} is underestimated. Using V_{GL} difference of 0.8 V, the L_{met} deviations (L_{error}) are smaller than 0.01 μm. Besides, the L_{met} derived from different T_L are also self-consistent, as shown in Fig. 2(b). Note that the T_L/T_F value for measurement should not be too small to make the real T_L value generated by the pulse generator much smaller than expected, otherwise, serious error will appear. In this paper, the charge-pumping currents measured under $T_L = 0.5$ μs and larger $|V_{SUB}$ are slightly smaller than expected (the pulse generator generated T_L is smaller than 0.5 μs), therefore, the calculated L_{met} is slightly larger than those derived from $T_L = 1$ μs and 2 μs. The accuracy of the proposed new method becomes worse than the multidevice method (0.01 μm accuracy) [5], because the L_{error} induced by the charge-pumping current measurement cannot be ignored. However, the current measurement induced deviations are smaller than 0.01 μm, 0.02 μm accuracy still can be achieved easily using the proposed new method.

IV. CONCLUSIONS

In this paper, a novel charge-pumping method using a single device is proposed to determine the metallurgical channel length of MOSFET's, in which the charge-pumping current related to the local area of an n-channel MOSFET can be derived from the charge-pumping currents measured with different V_{GL} and T_L. Comparing with the multidevice method, the newly developed method is shown to be relatively simple because only a single MOSFET and its measurement are needed. Moreover, the proposed method is shown to be accurate and self-consistent. In addition, the novel method can be applied to p-channel MOSFET's by determining the edges of the effective area from the critical surface electron concentration (n_c) at V_{GH}, and $\Delta(I_{cp}/f)$ in (5) should be derived from the charge-pumping currents measured under different V_{GH} and T_H with the same S_R, S_F, and V_{SUB}.

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