Solid-State Electronics 54 (2010) 635–641

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Parameter extraction in polysilicon nanowire MOSFETs using new double integration-based procedure

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ARTICLE INFO

Article history:
Received 7 October 2009
Received in revised form 21 December 2009
Accepted 21 January 2010
Available online 12 February 2010

The review of this paper was arranged by A. Zaslavsky

Keywords:
Parameter extraction
Threshold voltage
Subthreshold Slope
Double integration
Successive integration
Polysilicon
Nanowire
MOSFETs
Noise reduction

ABSTRACT

A new double integration-based method to extract model parameters is applied to experimental polysilicon nanowire MOSFETs. The threshold voltage and Subthreshold Slope factor are extracted from noisy measured current–voltage characteristics. It is shown that the present method offers advantages over previous extraction procedures regarding data noise reduction. In addition, the normalized mutual integral difference operator method is scrutinized and an improvement of the method is presented.

1. Introduction

Some of the more promising devices, being considered as possible alternatives to conventional CMOS, are monocrystalline double- and surrounding-gate MOSFETs [1–5]. At the same time, amorphous silicon (a-Si) thin-film transistors (TFTs) have traditionally dominated display applications, but today there is a growing need for better performance than what a-Si technology can provide. Consequently, polycrystalline silicon (poly-Si) TFTs are also receiving a great deal of attention as alternatives for large-area, low cost displays, as well as for other 3-D and large-area electronics applications. However, the performance of conventional planar poly-Si TFTs is still significantly impaired by the abundance of grain boundary defects in the polysilicon film [6]. These defects disturb carrier transport and particularly give rise to high Subthreshold Slope factor and off-state leakage current.

Many polysilicon MOSFET applications require reducing the amount of defects present in the channel body in order to decrease their harmful impact on the device's performance. Several technologies have been proposed to increase the polysilicon film grain size. They include excimer laser annealing [7] and metal-induced lateral crystallization [8], among others.

An interesting alternative to increasing grain size is to reduce the influence of grain boundaries by significantly shrinking the channel body size. The use of polycrystalline nanowire (NW) channel structures seems to be an appealing course of action towards that objective, since the total number of defects decreases significantly when the NW cross section is decreased. In that line, several NW polysilicon MOSFETs have been reported [9–14]. Polycrystalline long-channel ultra-thin body surrounding-gate NW MOSFETs have been proposed and fabricated [15,16] for flexible macroelectronics, as well as for other unconventional applications such as highly sensitive biosensors [17,18].

Modeling the phenomenology specific to polysilicon MOSFETs has been a topic of research for the last three decades [19,20].

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0038-1101/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2010.01.011

Although the present dominating trends point towards continuous models and away from regional approximation-based models, regional parameters such as threshold voltage and Subthreshold Slope (SS) factor are still considered very important for quality and reliability assessment purposes [21–24].

In the present paper we present a new integration-based method to extract the threshold voltage and SS factor of MOSFETs. This method is applied to measured characteristics of experimental polysilicon nanowire MOSFETs. Other methods are also scrutinized in Section 8.

2. Current model

The transfer characteristics in the weak inversion or subthreshold region of most MOSFETs may be modeled by an exponential function of the gate voltage of the form [25]:

$$I_{Dw} = I_o \exp\left(\frac{V_G}{n v_{th}}\right), \tag{1}$$

where I_0 is some global coefficient, $v_{th} = k_B T/q$ is the thermal voltage, V_G is the externally applied gate-to-source voltage, and n is the so-called subthreshold ideality factor. The subscript w in I_{Dw} refers to the drain current in the weak inversion region.

On the other hand, the strong inversion region at low drain voltage exhibits a super linear behavior with V_G and a linear behavior with V_D, that can be modeled by a power law, or monomial type, equation of the form [26]:

$$I_{Ds} = K(V_G - V_{TS})^m V_D, \tag{2}$$

where V_D is the externally applied drain voltage, K is a global conduction coefficient, m is the monomial's order, usually around 2, which reflects the distribution of states in the conduction band tail, and V_{Ts} is the $I_{Ds} = 0$ intercept, which can be viewed as a "strong inversion region-defined" threshold voltage. In this case, the subscript s denotes that the equation is valid in the strong inversion region.

3. Previous method

An integration-based method was proposed in 2001 for extracting model parameters of non-crystalline MOSFETs biased in the saturation region [26]. Its mathematical nature lessens the effect of data noise, in contrast to traditional derivative-based procedures which inherently worsen the data noise problem. The auxiliary function used in that method had been originally proposed in 1999 by our group to extract the model parameters of PN junctions at very low forward voltages [27]. The auxiliary function has the form:

$$H_1(V_G, I_D) = \frac{\int_{V_{Glow}}^{V_G} I_D(V_G)dV_G}{I_D - I_{low}}, \tag{3}$$

where $I_{low} = I_D\ (V_G = V_{Glow})$, and V_{Glow} is the lower limit of integration. The value of V_{Glow} must be selected such that Eq. (1) is valid at this point; i.e., the current is exponentially dependent on gate bias.

Substituting (1) into (3) and performing the indicated integration we get for the weak inversion, or subthreshold, region:

$$H_{1W}(V_G, I_D) = \frac{n v_{th} I_0 \left[\exp\left(\frac{V_G}{n v_{th}}\right) - 1\right]}{I_0 \left[\exp\left(\frac{V_G}{n v_{th}}\right) - 1\right]} = n v_{th}, \tag{4}$$

which is a constant value that we will refer to as H_{weak} from now on.

Substituting (2) into (3) and performing the indicated integration we get for the strong inversion region:

$$H_{1S}(V_G, I_D) = \frac{V_G - V_{Ts}}{m+1}, \tag{5}$$

which is a linear equation on V_G with a reciprocal slope of $m + 1$.

This auxiliary function H_1 defined in (3), which can be obtained by numerical integration of the $I_D - V_G$ transfer data measured at a small constant V_D, may be used to readily extract parameters I_0, n, m, and V_{Ts} by means of (4) and (5). The use of H_1 already is an improvement over derivative-based methods regarding data noise reduction. However, because H_1 still contains the possibly noisy raw current data in the denominator of (3), we propose the use of another auxiliary function to further improve the noise immunity of the procedure.

4. The new auxiliary function

The idea suggested by (3) may be taken one step further with the purpose of reducing even more the effect of data noise. To that end, let us define another function, H_2, based on successive double integration, to be used as an alternative to (3):

$$\begin{aligned} H_2(V_G, I_D) &\equiv \frac{\int_{V_{Glow}}^{V_G} \int_{V_{Glow}}^{V_G} I_D(V_G)\,dV_G\,dV_G}{\int_{V_{Glow}}^{V_G} I_D(V_G)\,dV_G - \int_{V_{Glow}}^{V_G} I_D(V_G = V_{G_{low}})\,dV_G} \\ &= \frac{\int_{V_{Glow}}^{V_G} \int_{V_{Glow}}^{V_G} I_D(V_G)\,dV_G\,dV_G}{\int_{V_{Glow}}^{V_G} I_D(V_G)\,dV_G - I_{low} V_G}. \end{aligned} \tag{6}$$

Replacing (1) into (6) and solving the integral yields for the subthreshold region:

$$H_{2w}(V_G, I_D) = \frac{n v_{th} I_{low} \left\{ n v_{th} \left[\exp\left(\frac{V_G}{n v_{th}}\right) - 1\right] - V_G \right\}}{n v_{th} I_{low} \left[\exp\left(\frac{V_G}{n v_{th}}\right) - 1\right] - I_{low} V_G} = n v_{th}, \tag{7}$$

which is the exact same result obtained in (4) using H_1. However, as will be confirmed later, the use of H_2 provides better noise immunity than H_1.

Replacing the strong inversion transfer Eq. (2) into (6) and solving the integral yields:

$$H_{2S}(V_G, I_D) = \frac{V_G - V_{Ts}}{m+2}, \tag{8}$$

which is a linear equation on V_G with a reciprocal slope of $m + 2$, in a similar fashion as H_{1s} in (5), except that in this case the reciprocal slope is $m + 2$.

5. Extraction procedure

The procedural sequence used to extract the parameter values proceeds as follows:

1) Numerically calculate the first and second integrals versus V_G of the measured $I_D(V_G)$ at low V_D. With these calculate function H_2 using (6).
2) Select an appropriate linear range of V_G in the strong inversion region to fit equation H_{2s} in (8) to the calculated H_2 data.
   a Extract the values of m and V_{Ts} from the linear fit.
   b Calculate K with (2) using the two extracted values of of m and V_{Ts}.

3) Determine H_{weak} as the value of H_2 in a range of the weak inversion region where it remains approximately constant.
4) Calculate the phenomenological V_T as the value of V_G corresponding to the intersection of H_{weak} and H_{2s}.