Optimization-based Determination of TFT contact Resistances in Python

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Abstract

The paper presents an optimization-based methodology for the determination of thin-film transistors series contact resistances. The implementation of the proposed methodology in Python is presented. The validity of results obtained against experimental devices characteristics is demonstrated. The advantage and limitations of the proposed methodology is also discussed.

Keywords—TFTs, compact model, contact resistances

I. INTRODUCTION

Due to the wide spread use of thin-film transistors (TFT) in a wide range of applications e.g., displays, radio-frequency identification tags (RIFID), or flexible electronics [1] a strong effort has been paid to the development of TFT compact models, [2]. In [3] a model-oriented methodology enabling the automatic determination of TFT parameters and its implementation in Python is presented. This paper considers an extension of this previous methodology, where the TFT contact resistances are also considered.

Section II considers the description of a TFT simple model, where the effects of nonlinearities arising from contact resistances are duly considered [4]. In this section, a previously proposed methodology for the evaluation of the model parameters is also described. A new methodology for the evaluation of TFT parameters will be described in Section III, which will prove to be more robust against the noisy subthreshold TFT transfer characteristic. The implementation of the proposed methodology in Python is described in Section IV. Section V is devoted to the validation of the results obtained with the proposed methodology. In this section, three TFT sets will be considered, and a brief comparison between measurement results and device characteristics obtained with the present work will be presented. Finally, conclusions are driven in Section VI

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II. THIN FILM TRANSISTOR MODEL

Although the transport characteristics of TFTs are very different for the different active materials, the current-voltage characteristic of these was initially evaluated using the MOSFETS Schokley model. In [4] a more accurate expression is proposed for TFT in saturation, and is given by:

$$I_{Dsat} = K(V_{GS} - V_T)^m, \tag{1}$$

given that,

$$K = \frac{W}{L_{eff}} \frac{\mu_0}{{V_{AA}}^{\gamma}} C_i \alpha \tag{2.a}$$

$$m = 2 + \gamma \tag{2.b}$$

where μ_0 is the carrier mobility at low bias, γ is the mobility enhancement factor, V_{AA} is a fitting parameter and α_s is also a fitting parameter that relates the saturation voltage overdrive. Should the contact resistances be considered, as illustrated in Figure 1, then the analytical expression for the drain current should reflect its dependence on the intrinsic voltages between the gate and source, V_{gs} and between the drain and the source, V_{ds}. These intrinsic voltages may be obtained with

$$V_{gs} = V_{GS} - I_D . R_s \tag{3.a}$$

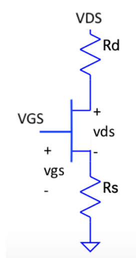

Fig. 1: TFT with parasitic contact resistances. Adapted from [4].

$$V_{ds} = V_{DS} - I_D.(R_D + R_S), \quad (3.b)$$

where V_{GS} and V_{DS} are the externally applied voltages between gate and source and between drain and source respectively. The drain current will, therefore, by obtained with

$$I_D = \mathrm{K}(V_{GS} - I_D R_S - V_t)^m. \quad (4)$$

For the evaluation of the series source contact resistance an auxiliar function H is evaluated with

$$H = \frac{\int_0^{V_{GS}} I_D \, dV_{GS}}{I_D}, \quad (5)$$

and may be evaluated with

$$H = \frac{R_s I_D (m-1)}{2(m+1)} + \frac{V_{GS} - V_t}{(m+1)}, \quad (6)$$

which will be used for the determination of the model parameters, trough fitting process to experimental data. Initially, the derivative of H and I_D with respect to V_{GS} is evaluated and then dH/dV_{GS} against dI_D/dV_{GS} is used for obtaining m and Rs. Then, using (7), Vt is determined. At last, K is obtained with

$$K = \frac{I_D}{(V_{GS} - V_T - R_S I_D)^m}. \quad (7)$$

This process yields quite accurate results, provided that the experimental data is carefully chosen, as will be illustrated in section IV.

III. TFT Model Parameter Evaluation

In this Section, an alternative methodology for the automatic evaluation of TFT model parameters, including the determination of the parasitic contact resistance between gate and source will be presented. The implementation of the proposed methodology in Python will also be presented.

A. Parameter Evaluation Methodology

For the automatic evaluation of the TFT model parameters, an optimization-based methodology is considered, which will be developed in two steps. The first step of the proposed methodology, considers the evaluation of the power parameter, m, through the evaluation of I_D/gm. From (4), the derivative of the current I_D with respect to V_{GS} is given by

$$\frac{dI_D}{dV_{GS}} = \mathrm{K}\, m\, (V_{GS} - I_D R_S - V_t)^{m-1} \left(1 - R_S \frac{dI_D}{dV_{GS}}\right). \quad (8)$$

Hence,

$$gm = \frac{\mathrm{K}\, m\, (V_{GS} - I_D R_S - V_t)^{m-1}}{1 + \mathrm{K}\, m\, (V_{GS} - I_D R_S - V_t)^{m-1}}, \quad (9)$$

Should the auxiliar function, Y, given by

$$Y = \frac{I_D}{gm}, \quad (10)$$

be considered, then

$$Y = \frac{V_{GS} - V_t + I_D R_S (m-1)}{m}. \quad (11)$$

It is to be noted, that the particular case where the contact resistance is neglected, i.e. $Rs=0$, function Y will become the well-known relation considered in [3]. In this general case, it may be considered that the dependence of Y on V_{GS} follows a line with slope $1/m$. Once function Y is numerically obtained from experimental data, then by fitting it to a straight line, will lead to the determination of m. After the value of parameter m is obtained, the remaining parameters, i.e., K, Vt and Rs are obtained by fitting (4) to the experimental transfer characteristic of the device.

B. Automatic parameter evaluation in Python

The Python script developed starts by obtaining the TFT characteristics from the files automatically generated from the measurements on implemented devices. Then, from the transfer characteristic, the corresponding differential conductance, g_m is numerically evaluated, and the characteristic I_D/g_m is obtained. It is to be noted, however, that special attention should be paid to the elect the gate to source voltage range for which the derived expression of I_D/gm is valid. As illustrated in figure 2, for very small values of V_{GS} a high dispersion of values for the I_D characteristic is observed and these values should not be taken into consideration. The typical behaviour I_D/gm is also depicted in Figure 2, where the numerically evaluated I_D/gm obtained from the experimental results are represented in blue. As duly illustrated, the expected linear relation of I_D/gm with respect to V_{GS}, will only be observed for values of the gate to source above a threshold, which correspond to the values where (4) is valid.

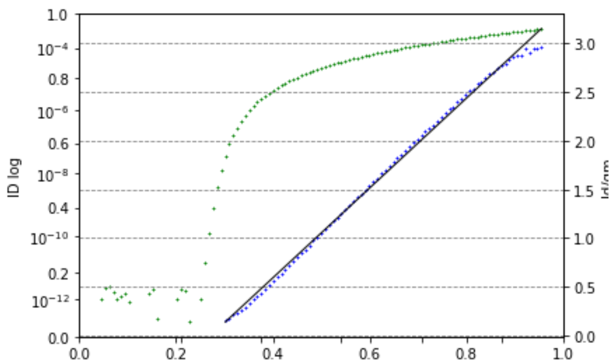

Fig. 2 Typical behaviour of I_D and I_D/gm

```
V1=VG_sat
I1=ID_sat
Imin=1e-9
I_i=np.where(I1>Imin)[0]
init=I_i[0]
gm=np.diff(I1[init:])/np.diff(V1[init:])
Y=I1[init+1:]/gm
def get_line(Vg,k,x,b):
          [lambda Vg: Imin,
           lambda Vg: k*(Vg-x)+b])

xx,xy=curve_fit(get_line,V1[init+1:],Y,ftol=1e-10)
m=1/xx[0]
```

List. 1 Python code for obtaining parameter *m*

The python code used for obtaining *m* is represented in Listing 1. For the selection of the V_{GS} range, only points where a minimum value for the output current, I_{min} is observed are considered. In the case illustrated, I_{min}=1nA was considered. The fitted characteristic for I_D/gm is also represented in Figure 2, in black, illustrating the accuracy of the results obtained.

The remaining parameters, i.e., *Vt*, *K* and *Rs* were then obtained with the python code represented in Listing 2, where the optimization process considers a piecewise function that accounts for the different operating regions of the device. In the first region the output current is considered with a fixed value equal to the value selected for I_{min}. In the second region, the output current is considered as given by (4), added to the value of I_{min} as a way of guaranting that the function representing the output current is continuous. As illustrated in Listing 2, the function *get_vt_k_Rs* considers two operating regions, where the value of *Vg* which determines the change between the two operating regions is a function of parameters, *Vt* and *Rs* that are to be evaluated. This approach ensures that the fitting process of (4) to the experimental data will consider only the appropriate TFT range of operation for the model to be valid.

Moreover, the fact that in (4) the transfer characteristic of the TFT is an implicit function will bring additional challenge to the

```
def get_vt_k_Rs(data,vt,Rs,k) :
     vg, id=data
     i_vg=vt+Rs*id
     vgi=np.where(vg>i_vg)
     init=vgi[0][0]
     return np.piecewise(vg, [vg <= i_vg,   vg>i_vg],
          [lambda vg: Imin,
          lambda vg: Imin+k*(vg-vt-Rs*id[init:])**ml])

xx,xy=curve_fit(get_vt_k_Rs,(VG_sat,ID_sat), ID_sat,
bounds=([-2,10,1e-8],[1,3000,1e-5]), ftol=1e-12)
Vt=xx[0]
Rs=xx[1]
 K=xx[2]
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List. 2: Python code for evaluating Vt, Rs and K

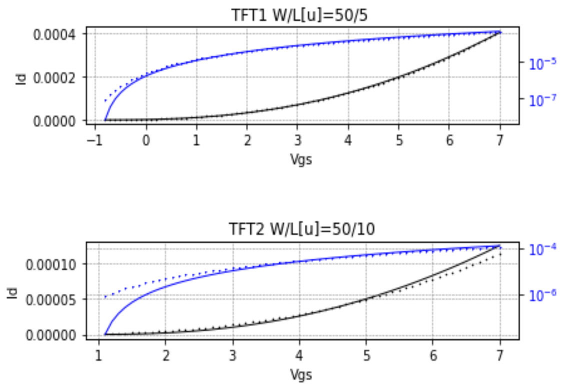

Fig. 3. Output characteristics for the TFT1 and TFT2

optimization process. Also, since the optimization process is three dimensional and non-convex, bounds to the several parameters had to be considered as a way of obtaining parameter values that are in line with their physical meaning. In the present case $-2.0 \leq V_t \leq 1.0$, $10 \leq R_s \leq 3000$ and $1.0e-8 \leq K \leq 1.0e-5$ were chosen. Finally, since the output currents to be fitted have very small values, the tolerance was also modified accordingly (i.e., *ftol=1e.12*).

IV. Working Examples

The proposed methodology was applied to two TFTs with the sizes table 1, where the model parameters obtained are also presented.

TABLE I. Model Parameters

	TFT1 W/L=50/5 [µm]	**TFT2 W/L=50/10 [µm]**
Vt	-0.909	0.959
m	2.624	2.414
Rs	1004.292	2947.76
K	2.037e-06	1.8752e-06

In Figure 3 the output charateristics obtained with the model and those obtained from measurements are represented, showing the good accuracy of the results obtained.

A Python script implementing the methodology proposed in [4] was also developed, and results obtained for TFT2 are represented in Table II. Due to implementation details, the selection of the experimental data to be fitted was not based on the definition of a minimum value for the current, I_{min}, but rather by retaining only the previously selected last points of the characteristic that ensured a linear *H* function.

TABLE II. Model Parameters with methodolog [4]

	TFT2 W/L=50/10 [µm]
Vt	0.959
m	2.414
Rs	2947.76
K	1.875e-06

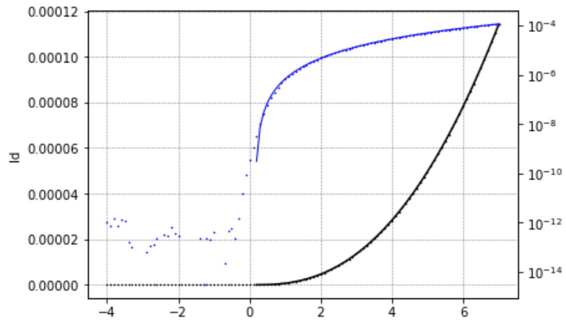

Fig. 4: Output charatceristics for TFT2 obtained with [4]

In Figure 4 the output charateristics obtained with the approach in [4] and those obtained from measurements are represented, showing the excellent accuracy of the results obtained.

A. Robustness of the Proposed Methodology

For a second validation, the robustness of the proposed methodology against the established value for *Imin* is investigated. The several values for *Imin* considered are represented on Table 2. In the same table, the values for the model parameters for TFT2, corresponding to the values for *Imin* considered are also represented.

TABLE III. MODEL PARAMETERS FOR DIFERENT IMIN

I_{min}	1e10	1e-9	1e-8	1e-7
Vt	0.951	0.959	0.958	0.958
m	2.425	2.414	2.394	2.393
Rs	2957.08	2947.76	2946.74	2946.39
K	1.743e-6	1.875e-6	2.055e-6	1.922e-6

From the values obtained, it may be easily concluded that the values for the threshold voltage, *Vt*, the power factor, *m,* and the parasitic series resistance*, Rs,* are not affected by the change in value for I_{min}. The value for parameter *K*, shows some variation with I_{min}, (i.e, from 1.743e-6 to 2.055e-6) that can however be considered as not very relevant.

For evaluating the robustness of the methodology in [4], three different situations were considered. For a transfer characteristic with 101 points, the first *nx* points were not considered. The results obtained are represented in Table IV.

TABLE IV. MODEL PARAMETERS OBTAINED WITH [4] FOR DIFERENT I_{MIN}

nx	41	42	43
I_{min}	3.32e-09	9.88e-9	2.62e-8
Vt	0.162	0.204	0.207
m	2.477	2.41	2.443
Rs	2957.08	301.47	1500
K	1.040e-06	1.411e-06	1.125e-06

It is to be noted that the variations considered, correspond to variatiation in I_{min} that are in line with those considered in the last three columns in Table III. The results obtained illustrate the high sensivity of this methodology on the range of values of the TFT transfer characteristic that are chosen to be considred in the optimization process.

V. CONCLUSIONS

In this paper a methodology for the automatic determination of TFT model parameters was presented., which that take into consideration the series parasitic resistance between the gate and the source of the transistor. The proposed methodology considers the determination of the power parameter, *m,* from the I_D/gm characteristic of the TFT. Then the remaining parameters are obtained from the transfer characteristic of the TFT. The robustness of the proposed methodology when applied to experimental data was compared with another approach proposed in the literature. The proposed methodology was implemented in a Python script which reads the files containing the devices output and transfer characteristics obtained from measurements and automatically evaluates the TFT model parameters. The graphical representation of the TFT characteristics obtained with the model, against those obtained from the measurements are also generated. The results obtained show a relevant accuracy and their robustness when applied to experimental data is duly demonstrated.

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