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A SIMPLE SEMI-ANALYTICAL MODEL FOR THE KINK EFFECT FOR THE INTRINSIC N-CHANNEL POLYSILICON THIN FILM TRANSISTORS

M. J. SIDDIQUI, S. QURESHI, S. M. ALSHARIFF

Electrical Engineering Department, College of Engineering, Taibah University,
Al-Madinah Al-Munawwarah, Saudi Arabia

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ABSTRACT

In order to improve the modeling of Polysilicon thin film transistors (Poly-Si-TFTs) a precise evaluation of the excess current due to impact ionization is needed. In this paper we have proposed a simple model for the excess current resulting from the impact ionization occurring at high drain biases. Model is based on the estimation of the electric field in the saturated part of the channel. The electric field in the saturated region is obtained by the solution of the two--dimensional Poisson's equation. The model is semi-analytical and uses only one fitting parameter which is desirable for circuit simulation. The simulation results with the developed impact ionization current model are in excellent agreement with the available experimental output characteristics of the intrinsic n-channel Poly-Si-TFTs.

1. Introduction

Recently the intrinsic polysilicon Thin Film Transistors (Poly-Si TFTs) have received considerable attention for large area electronics applications, in particular, active matrix liquid crystal display (AMLCD) applications like high definition television (HDTV), projection displays and portable devices. As a result of growing interest of Poly-Si TFTs in large area integrated electronics, there is need for accurate, simple analytical models for circuit design and simulations. It is desirable to have physical models employing minimum number of parameters which can be extracted easily.

The presence of high electric field in the Poly-Si TFT leads to the impact ionization in the vicinity of drain which results in significant increase in drain current as drain to source voltage is increased beyond drain to source saturation voltage V_{DSAT}. This effect is called the "kink" effect. The kink effect results in an increase of the output conductance and therefore, enhances power dissipation in case of digital circuits and degrades the switching characteristics, while in case of analog circuit applications, it reduces the maximum attainable gain as well as the common mode rejection ratio.

The kink effect has been investigated by several researchers [1–4] with the aid of two-dimensional numerical simulation, the nature of kink effect has been identified to be due to the impact ionization mechanism in the high field regime near the drain. The possible reason of the kink effect is bipolar effect similar to that floating body crystalline SOI MOSFET [5]. When the hole trapping states are low, the holes generated by the impact ionization, reach the source contact and reduce the potential barrier between source and body. This decreases the threshold voltage and increases the channel current. Because the source-body junction becomes forward biased, additional electrons are injected from the source to the body. If the channel is short enough, a significant fraction of these electrons do not combine with the holes in the channel and are collected by the drain. This creates the positive feedback and hence result in multiplication.

In this paper, we have proposed a simple model to estimate the excess current resulting from the impact ionization at high drain biases. The excess current due to kink effect is added to the drain current obtained by the surface potential based charge sheet model for the Poly-Si TFT presented in [6].

2. Model for the kink effect

The Poly-Si TFT goes into the saturation when $V_{DS} > V_{DSAT}$ as shown in Fig. 1a, where V_{DSAT} is the drain to source voltage (V_{DS}) at which Poly-Si TFT enters into saturation and it is given by:

$$V_{DAST} = V_{GS} - V_T \tag{1}$$

where V_T is the threshold voltage given by the relation:

$$V_T = V_{FB} + 2\phi_b + \frac{\sqrt{2\varepsilon_s q N_{eff} 2\phi_b}}{C_{ox}}. \tag{2}$$

The kink effect occurs for large drain to source voltages, when TFT is biased in saturation. It is modeled as an impact ionization in the pinch-off region of length ΔL as shown in Fig. 1b. For $V_{DS} > > V_{DSAT}$ impact ionization leads to avalanche multiplication and subsequent increase in drain current, which can be written as $\Delta I_{kink} = M \cdot I_{DSAT}$. Where M is the multiplication factor and is function of V_{DS}. The total drain current is given by:

$$I_D = I_{DSAT} + \Delta I_{kink} = I_{DSAT}(1 + M). \tag{3}$$

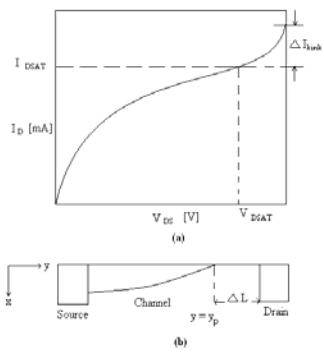

Fig. 1. Definition of I_{DSAT}, V_{DSAT} and ΔI_{kink} (a), pinch-off region (b).

The multiplication factor M can be given by:

$$M = \int_{y=y_p}^{y=L} \alpha_n dy \tag{4}$$

where a_n is a strong function of channel electric field E. The exact dependence of α_n on the electric field is complicated, however most commonly used expression is [7]:

$$\alpha_n = A_i \exp\left(\frac{B_i}{E}\right) \tag{5}$$

where A_i and B_i are called ionization constants [7]. For the evaluation of channel electric field E, we have to consider the saturation region. The saturation region can be described by two-dimensional Poisson's equation of the form:

$$\frac{\partial E_y}{\partial y} + \frac{\partial E_x}{\partial x} = \frac{\rho(x,y)}{\varepsilon_s} \tag{6}$$

where E_x and E_y are the transverse and longitudinal components of the electric field, respectively. $\rho(x,y)$ is the charge density in the semiconductor consisting of mobile charge density, n_m and trapped charge density, n_t. Integrating Eq. (5) with respect to x from the semi- conductor-insulator interface through the effective channel thickness δd, we obtain:

$$\left\langle \frac{\partial E_y}{\partial y} \right\rangle \delta d + E_x(\delta d) - E_x(0) = -\frac{q}{\varepsilon_s}(n_m + n_t)\delta d \tag{7}$$

where $\langle \partial E_y/\partial_y \rangle$ is the average of $\partial E_y/\partial_y$ over the channel thickness. In the strong inversion region the $n_m >> n_t$, the vertical electric field at $y = \delta d$ will be small compared to the vertical electric field at the interface, in which case $E_x(\delta d)$ can be neglected. Making substitution $\langle \partial E_y/\partial_y \rangle = \partial^2 V/\partial y^2$, where V is the average channel potential over the cross-section of the channel. Therefore, above equation can be written as:

$$\frac{\partial^2 V}{\partial y^2} + \frac{E_x(0)}{\delta d} = \frac{q}{\varepsilon_s}(n_m + n_t). \tag{8}$$

The electric field at the interface is obtained by equating the electric displacement of the two side of the semiconductor-insulator interface

$$\varepsilon_i E_i = \varepsilon_s E_s. \tag{9}$$

At the interface

$$E_x(0) = E_s = \frac{\varepsilon_i E_i}{\varepsilon_s} = \frac{\varepsilon_i V_{ox}}{\varepsilon_s t_{ox}}$$

and

$$C_{ox} = \frac{\varepsilon_i}{t_{ox}}, V_{ox} = V_{GS} - V_{FB} - \Psi_s - V,$$

therefore

$$E_x(0) = E_s = \frac{C_{ox}}{\varepsilon_s}(V_{GS} - V_{FB} - \Psi_s - V) \tag{10}$$

where Ψ_s is the surface potential at source end. From the condition of velocity saturation and current continuity, we know that the electron concentration is constant in the saturation region. Its value can be determined at the boundary point, $y = y_p$ (pinch-off), where the gradual channel approximation is still valid. At boundary point $y = y_p$, the channel potential $V = V_p$. Thus we can write the charge density Q_s at boundary point $y = y_p$ as:

$$Q_s = q(n_s + n_t \delta d) = \varepsilon_s E_s \tag{11}$$

where n_s is the electron sheet density in the channel. Using Eqs. (10) and (11), we can write:

$$n_s = \varepsilon_s \frac{C_{ox}}{q\varepsilon_s}(V_{GS} - V_{FB} - \Psi_s - V_p) - n_t \delta d \tag{12}$$

The combination of above equations leads to the following second order differential equation for the channel potential in the saturation region:

$$\frac{\partial^2 (V - V_p)}{\partial y^2} - \frac{(V - V_p)}{\gamma^2} = 0 \tag{13}$$

where $\gamma = \sqrt{\varepsilon_s \delta d / C_{ox}}$ and known as characteristics length. It should be noted that the solution of Eq. (13) is very sensitive to the magnitude of γ. Hence γ should be treated as a fitting parameter, rather than calculating its value from above relationship. The general solution above second order differential equation can be written as:

$$V(y) = V_p + Ae^{(y-y_p)/\gamma} + Be^{-(y-y_p)/\gamma}. \quad (14)$$

The coefficients A and B are determined from the boundary conditions, i.e. from the requirement that V and E are continuous at $y = y_p$ with values as $V_p = V_{DSAT}$ and $E = E_{SAT}$, respectively. Where E_{SAT} represents the channel electric field at which carriers reach velocity saturation and corresponding voltage at that point is the saturation voltage V_{DSAT}. The values A and B are $V_\gamma/2$ and $-V_\gamma/2$, respectively, where $V_\gamma = \gamma E_{SAT}$. This leads to:

$$V(y) = V_p + \frac{V_\gamma}{2} e^{(y-y_p)/\gamma} - \frac{V_\gamma}{2} e^{-(y-y_p)/\gamma}. \quad (15)$$

The potential $V(y)$ and electric field $E(y)$ in the saturated part of the channel is given by:

$$V(y) = V_p + \frac{V_\gamma}{2} \sinh\left(\frac{y-y_p}{\gamma}\right) \quad (16)$$

and

$$E(y) = E_{SAT} \cosh\left(\frac{y-y_p}{\gamma}\right), \quad (17)$$

respectively.

The above equations can be written as:

$$V(y') = V_p + \frac{V_\gamma}{2} \sinh\left(\frac{y'}{\gamma}\right) \quad (18)$$

and

$$E(y') = E_{SAT} \cosh\left(\frac{y'}{\gamma}\right) \quad (19)$$

where y' is the distance along the channel with $y' = 0$ representing the start of the velocity saturation region.

Using the above relations for the electric field in saturated part of the channel and substituting in Eqs. (4) and (5) and changing the variable of integration dy' to dE and integrating from E_{SAT} to E_m (the maximum electric field which occurs at the drain end), we can write the expression for the multiplication as:

$$M = A_i \gamma \int_{E_{SAT}}^{E_m} \frac{1}{\sqrt{E^2 - E_{SAT}^2}} \exp\left(\frac{B_i}{E}\right) dE. \quad (20)$$

The above integral has no closed form solution. However, it can be approximated fairly accurately as [7]:

$$M = A_i \gamma \frac{1}{\sqrt{E^2 - E_{SAT}^2}} \frac{E_m^2}{B_i} \exp\left(-\frac{B_i}{E}\right). \quad (21)$$

The maximum field E_m can easily be obtained from Eqs. (18) and (19) by replacing $V = V_{DS}$. Since in general, E_{SAT} is small compared to other term. We can neglect E_{SAT} and approximate value of E_m can be written as follows:

$$E_m = \frac{V_D - V_{DS}}{\gamma}. \quad (22)$$

This results in the following expression for

$$M = \frac{A_i}{B_i} (V_{DS} - V_{DSAT}) \exp\left(\frac{-\gamma B_i}{V_{DS} - V_{DSAT}}\right). \quad (23)$$

Above equation may be written as:

$$M = \frac{V_{DS} - V_{DSAT}}{V_K} \exp\left(\frac{-\lambda_k}{V_{DS} - V_{DSAT}}\right) \quad (24)$$

where V_K and λ_K are the fitting parameters.

3. Charge sheet model including kink effect

At high drain to source voltage i.e. $V_{DS} \geq (V_{GS} - V_T)$, the total drain current in the channel is the sum of drift, diffusion and the excess current due to kink effect. Therefore, the total current can be written as:

$$I_D = I_{drift} + I_{diff} + \Delta I_{kink} \quad (25)$$

where the currents I_{drift} and I_{diff} are given by Eqs. (20) and (21) in [6], respectively. The current due to kink effect is:

$$\Delta I_{kink} = M \cdot I_{DSAT} \quad (26)$$

where M is given by Eq. (24) and I_{DSAT} is the saturated drain current when TFT enters into saturation region i.e. when $V_{DS} \geq (V_{GS} - V_T)$.

4. Results

The kink model along with the charge sheet model described in [6] has been verified on four n-channel Poly-Si TFTs. The physical data for these four n-channel Poly-Si TFTs such as gate length, gate width, oxide thickness and thin film thickness are given in Table 1. The details of four n-channel TFTs are as follows. The TFT1 and TFT2 were fabricated using Low Pressure Chemical Vapor Deposition (LPCVD) technique described in [5]. TFT3 was fabricated by pyrolysis of Si_2H_6 in a Ultra High Vacuum Chemical Vapor Deposition (UHVCVD) reactor and subsequently furnace crystallized [8]. TFT4 was fabricated using Laser Annealing method described in [9]. The parameters associated with charge sheet model for n-channel Poly-Si TFTs are given [6]. The parameters used for the kink model for n-channel Poly-Si TFTs are given in Table 2. It is observed that the parameter λ_K is

the same for all n-channel Poly-Si TFTs, only the parameter V_K is changing. That is our model uses only one fitting parameter which is desirable for circuit simulation. The above proposed kink model has been verified on the four n-channel Poly-Si TFTs output characteristics as shown in Fig. 2 and Fig. 3. The curves show the drain current obtained from the proposed model and symbols show the experimental data obtained from [5], [8], [9]. A reasonable good match is observed in the linear, saturation and kink regimes.

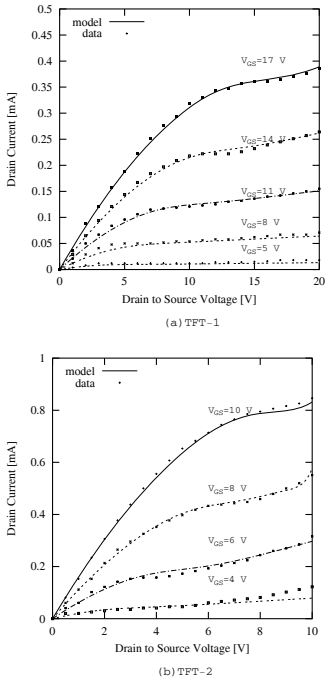

Fig. 2. Output characteristics of TFT1 and TFT2. Curves indicate model results and symbols indicate experimental data.

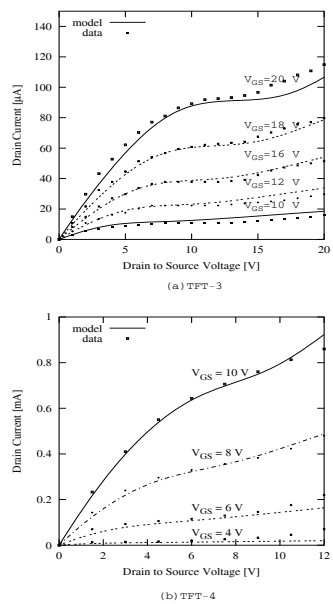

Fig. 3. Output characteristics of TFT3 and TFT4. Curves indicate model results and symbols indicate experimental data.

Table. 1. The physical data for n-channel Poly-Si TFTs.

Physical parameter	TFT1	TFT2	TFT3	TFT4
Gate length [cm]	$50{\cdot}10^{-4}$	$6{\cdot}10^{-4}$	$20{\cdot}10^{-4}$	$6{\cdot}10^{-4}$
Gate width [cm]	$50{\cdot}10^{-4}$	$50{\cdot}10^{-4}$	$30{\cdot}10^{-4}$	$50{\cdot}10^{-4}$
Insulator thickness [cm]	$10{\cdot}10^{-6}$	$10{\cdot}10^{-6}$	$12{\cdot}10^{-6}$	$15{\cdot}10^{-6}$
Thin film thickness [cm]	$10{\cdot}10^{-6}$	$10{\cdot}10^{-6}$	$10{\cdot}10^{-6}$	$3.5{\cdot}10^{-6}$

Table. 2. The kink parameters for n-channel Poly-Si TFTs.

Parameter	TFT1	TFT2	TFT3	TFT4
V_K	43	07	18	9.5
λ_K	0.91	0.91	0.91	0.91

5. Conclusion

The kink model proposed in this paper has been verified on intrinsic p-channel Poly-Si TFTs and has a reasonable good match with experimental data. This physics based kink model uses only one fitting parameter which is desirable for circuit simulation.

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