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Surface potential calculation and drain current model for junctionless double-gate polysilicon TFTs

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Surface potential is a key parameter in evaluating the DC property of thin-film transistors (TFTs). In this paper, for the junctionless symmetric double-gate polysilicon TFTs, a physical-based explicit calculation to surface potential has been derived. Incorporating impurity concentration, mobile charge and trap density into Poisson’s equation, a closed form of band bending as a function of gate voltage is obtained and demonstrated as an accurate and computationally efficient solution. Based on surface potential, a drain current model for long-channel devices is provided in explicit forms. Furthermore, it is verified successfully by comparisons with both 2D numerical simulation and experimental data in different operation regions.

I. INTRODUCTION

A significant distinction between junctionless (JL) and inversion mode (IM) of polysilicon thin-film transistors (poly-Si TFTs) is that the channel of JL device is heavily doped of the same type and a similar magnitude of concentration as the source and the drain. Thus, it can skip junction formation issues and greatly simplify fabrication. Recently, the JL poly-Si TFTs have been shown as attractive devices because they possess excellent turn-on and output characteristics, an improved subthreshold swing, a large ON-current, a high ON/OFF-current ratio, etc. Also, it is feasible to apply JL scheme for large-area electronics as well as 3D stackable poly-Si based electronics.

As a counterpart of JL poly-Si TFTs, JL MOSFETs have several compact models. A compact model, unlike a simple device model or a comprehensive computer simulation model used for understanding the device physics, provides both accuracy and computational efficiency due to the limited simulation time. Model based on charge density has been developed for JL symmetric double-gate (SDG) MOSFETs, which applies a coarse finite-different approximation. Furthermore, it is shown that the model is valid in all regions of operation, from fully depletion to accumulation. Also, for a SDG JL MOSFET, Taur et al. proposed a physical relation between surface potential and potential at the center film for a given gate voltage, but an explicit solution cannot be obtained. Subsequently, a surface-potential-based model for SDG JL MOSFETs was established, and simplified calculations for surface potential and drain current were carried out in different operation regions. Although this regional approximation has its limitation, it comes out that the approximations so far are quite accurate and well sounded.

Due to the further exploitation and the use of the JL poly-Si TFTs in circuits, it is mandatory to develop the physics-based and feasible device model. Nonetheless, few studies in literature have been carried out to develop a physical and compact model for the JL poly-Si TFTs. In this work, to develop a complete and compact model, we present an explicit scheme to efficiently compute the surface potential by using the regional approach, which is capable of reducing computation time and providing excellent accuracy. Further calculations for drain current have been derived to well
predict the DC characteristics in a wide range of operation regions, i.e., from subthreshold, partial
depletion, to accumulation, and from linear to saturation.

II. CALCULATION OF SURFACE POTENTIAL

As shown in Fig. 1, we assume a junctionless symmetric double-gate poly-Si TFT with channel
length \( L \), polysilicon film thickness \( t_{\text{film}} \), oxide thickness \( t_{\text{ox}} \), and a uniform n-type impurity
concentration \( N_d \) within the channel and S/D regions. The polysilicon material has an exponential
acceptor-like deep state density as \( g(E) = g_d \exp\left(\frac{E - E_C}{q\phi_G}\right) \), where \( g_d \) and \( q\phi_G \) are the deep state density
at the conduction band edge \( E_C \) and its inverse slope, respectively. These trap-related parameters can
be determined by the field-effect conductance method,8 CV measurements,9 fitting to experimental
data,10 etc.

Although junction-based and junctionless devices are very similar, the operating principle of
junctionless poly-Si TFTs is quite different from that of the conventional IM TFTs. In subthreshold
region \( V_{gs} \leq V_{th} \), the gate field pushes the majority carriers away from the surface, and a highly
doped channel of JL device is fully depleted (FD). Moreover, the device turns off by making the
channel fully depleted. As the gate voltage increases \( V_{th} < V_{gs} < V_{fb} \), the electric field reduces and
a neutral region is created at the device center. In the flatband condition \( V_{gs} = V_{fb} \), the depletion
width reduces to be zero and a completely neutral film is formed. Thereafter, by increasing the gate
voltage further \( V_{gs} > V_{fb} \), the majority carriers accumulate and essentially flow at the surface,
which is different from the minority carriers of the IM devices. Thus, the device is on.

If energy zero point locates at midgap, the one-dimensional Poisson equation in the direction
of film thickness can be written as

\[
\frac{d^2 \phi}{dx^2} = \frac{q}{\varepsilon_{si}} \left[ N_d \exp\left(\frac{\phi - V}{\phi_t}\right) - N_d + N_{\text{r0}} \exp\left(\frac{\phi - V}{\phi_G}\right) \right] \tag{1}
\]

where \( N_{\text{r0}} = g_d \frac{\pi k T}{\sin(\pi \phi_t/\phi_G)} \exp(\phi_{f0}/\phi_G) \), when \( \phi_t < \phi_G \).11 Herein,
\( \phi \) is the electrostatic potential, \( \varepsilon_{si} \) is the polysilicon material permittivity, \( q \) is the electronic charge,
\( V \) is the quasi-Fermi potential, \( \phi_t \) is the thermal voltage, and \( E_{f0} \) is the Fermi potential: \( E_{f0} = \phi_t \ln(N_d/n_i) \). We would like to stress that, except the sign of the ionized donor charge density \( N_d \),
Poisson’s equation in (1) is the same as that in conventional IM poly-Si TFTs. Nevertheless, the principle of operation is totally different. Although an accurate calculation for the undoped IM poly-Si TFTs has been obtained, this approach is linked to the IM case, and the solution for surface potential of JL poly-Si TFTs requires different modeling methods. This is developed as the following.

Equation (1) must satisfy the following boundary conditions:

\[
\frac{d\phi}{dx}\bigg|_{x=0} = 0 \quad \phi\left(\frac{t_{film}}{2}\right) = \phi_s
\]

where \(x = \pm t_{film}/2\) and \(x = 0\) correspond to polysilicon/SiO\(_2\) interfaces and the film center, respectively.

Integrating (1) once with the boundary conditions, one obtains

\[
E(\phi) = \frac{d\phi}{dx} = \text{sgn}(\phi) \sqrt{\frac{2q}{\varepsilon_{si}}} \\
\times \left\{ N_d \phi_0 \left[ \exp\left(\frac{\phi - V}{\phi_t}\right) - \exp\left(\frac{\phi_0 - V}{\phi_t}\right)\right] - N_d (\phi - \phi_0) \right. \\
+ N_{int} \phi_G \left[ \exp\left(\frac{\phi - V}{\phi_G}\right) - \exp\left(\frac{\phi_0 - V}{\phi_G}\right)\right]\right\}^{1/2}
\]

where \(\phi_0\) is the potential at the center of film. Note that, in the subthreshold mode, the gate field is of opposite sign and pushes the electrons away from the surface. In the partially depletion (PD) mode, the field is relatively small. While in the accumulation case, JL device eventually reverses the field but the field magnitude remains much smaller than that of IM devices.

Using the Gauss’ law at the interface, the relation of \(\phi_s\) and \(\phi_0\) with gate bias \(V_{gs}\) becomes

\[
V_{gs} - V_{fb} - \phi_s = \frac{\varepsilon_{si}}{C_{OX}} E(\phi_s)
\]

where \(V_{fb}\) is the flatband voltage, which can be estimated as: \(V_{fb} = -\frac{E_g}{2} + E_f - \frac{Q_{fix}}{C_{OX}}\). Herein, \(Q_{fix}\) is the fixed oxide charge and assumed to be zero. In addition, the threshold voltage \(V_{th}\) is expressed as: \(V_{th} = V_{fb} - \frac{qN_{int}t_{film}}{2} \left(\frac{t_{film}}{4\varepsilon_{si}} + \frac{1}{C_{OX}}\right)\).

Equation (4) establishes an implicit relationship between \(\phi_s\) and \(V_{gs}\). In general, (4) cannot be calculated in a closed form. In fact, surface potential \(\phi_s\) can be only solved accurately using an iterative numerical approach which poses a severe computational burden. An explicit approximation of (4) can be obtained by using a regional approach and making some assumptions. In general, a distinction can be made in three different operation regions, namely accumulation, partial depletion and fully depletion.

A. Potential in accumulation

In the case of accumulation \((V_{gs} > V_{fb})\), a high mobile carrier density exists in channel, and screens the electric field. Therefore, \(\phi_0\) is assumed to be frozen at \(\phi_0 \approx V_{in}\) in accumulation. Furthermore, we propose to omit the contributions of donor and trap states due to the accumulation of electrons. Consequently, (4) simplifies into

\[
V_{gs} - V_{fb} - \phi_s = \sqrt{\frac{2q\varepsilon_{si}N_d\phi_t}{C_{OX}}} \left[ \exp\left(\frac{\phi_s - V}{\phi_t}\right) - 1\right]^{1/2}.
\]

Neglecting “-1” term in (5), Eq. (5) is the same as the strong inversion case in IM MOSFETs, and therefore, surface potential in accumulation denoted by \(\phi_s^a\), can be solved as

\[
\phi_s^a = V_{gs} - V_{fb} - 2\phi_t W_0 \left[ \frac{G\sqrt{\Delta}}{2} \exp\left(\frac{V_{gs} - V_{fb}}{2\phi_t}\right) \right]
\]
where $G = \frac{\sqrt{2q\varepsilon_s N_{t,0}\Delta}}{C_{ox}}$, $\Delta = \exp(-V/\phi_t)$, and $W_0$ stands for the principal branch of the Lambert $W$ function.

Because of neglecting “-1” term in (5) before attempting the solution (6), errors are introduced around $V_{fb}$, where surface potential should approach $V$, i.e., $\phi_s^x \approx \phi_0 \approx V$, due to the flatband condition. As a consequence, for a more accurate result, we modifies the above solution to

$$
\phi_s^x = V_{gs} - V_{fb} + \delta - 2\phi_t W_0 \left[ \frac{G \sqrt{\Delta}}{2} \exp \left( \frac{V_{gs} - V_{fb} + \delta}{2\phi_t} \right) \right]
$$

(7)

where $\delta = G\phi_t + V$.

**B. Potential in partially depletion**

In the case of PD mode ($V_{th} < V_{gs} \leq V_{fb}$), the energy band bends up and the sign function in (3) becomes negative due to $\phi < 0$. Moreover, in this case, the mobile charge density is negligible with respect to the fixed charge density, and therefore, (4) becomes

$$
V_{gs} - V_{fb} - \phi_s = -\frac{\sqrt{2q\varepsilon_s}}{C_{OX}} \times \left\{ N_{t,0}\phi_t \left[ \exp \left( \frac{\phi_s}{\phi_t} \right) - \exp \left( \frac{\phi_0}{\phi_t} \right) \right] - N_d(\phi_s - \phi_0) \right\}^{1/2}
$$

(8)

where $N_{t,0} = N_{t,00} \exp(-V/\phi_G)$.

Replacing $-\phi_s$ by $\Phi_s$, leads to

$$
v_{gb} - \Phi_s = \frac{\sqrt{2q\varepsilon_s}}{C_{OX}} \times \left\{ N_{t,0}\phi_t \left[ \exp \left( \frac{-\Phi_s}{\phi_t} \right) - \exp \left( \frac{\phi_0}{\phi_t} \right) \right] + N_d(\Phi_s + \phi_0) \right\}^{1/2}
$$

(9)

where $v_{gb} = -(V_{gs} - V_{fb})$.

The normalized form of (9) can be written as

$$
(x_g - x_s)^2 = G_T^2[x_s + \theta \exp(-x_s) + A]
$$

(10)

where $x_g = v_{gb}/\phi_G$, $x_s = \Phi_s/\phi_G$, $G_T = \sqrt{2q\varepsilon_s N_d/\phi_G/C_{OX}}$, $\theta = N_{t,0}/N_d$, and $A = \phi_0/\phi_G - \theta \exp(\phi_0/\phi_G)$.

In the PD case, $\theta$ and $\Phi_s$ are small values due to the high level of $N_d$, and therefore, Taylor expansion (i.e., $\exp(-x_s) \approx 1 - x_s + x_s^2/2$) is applied to the solution of (10). As a result, (10) can be rearranged as

$$
ax_s^2 - bx_s + c = 0
$$

(11)

where $a = 1 - 0.5G_T^2\theta$, $b = 2x_s + G_T^2(1 - \theta)$, and $c = x_s^2 - G_T^2(A + \theta)$.

Here, following a mathematical procedure to obtain the solution of a quadratic equation, one derives

$$
x_s = \frac{-b + \sqrt{b^2 - 4ac}}{2a}
$$

(12)

Consequently, the surface potential in the PD mode (i.e., $\phi_s^P$) is determined as

$$
\phi_s^P = -x_s\phi_G.
$$

(13)
C. Potential in fully depletion

Limited to the case of fully depleted mode ($V_{gs} \leq V_{fb}$), namely subthreshold region, using the depletion approximation, we have

$$\alpha = \varphi_0 - \varphi_s \approx \frac{qN_d t_{film}}{8\varepsilon_{si}}. \quad (14)$$

It should be noted that (8) is also valid to the FD mode. Hence, (8) can be rewritten as

$$V_{gs} - V_{fb} - \varphi_s = -\sqrt{\frac{2q\varepsilon_{si}\alpha N_d}{C_{OX}}} \times \left\{ \frac{N_{ta}\Phi_G}{2\alpha N_d} \left[ 1 - \exp\left( \frac{\alpha}{\Phi_G} \right) \right] \exp\left( \frac{\varphi_s}{\Phi_G} \right) + 1 \right\}^{1/2}. \quad (15)$$

Since the film is heavily doped and $\varphi_s < 0$, the Taylor expansion of the argument inside the square root in (15) with only first-order terms allows (15) to be rewritten as

$$V_{gs} - V_{fb} - \varphi_s = -\sqrt{\frac{2q\varepsilon_{si}\alpha N_d}{C_{OX}}} \times \left\{ \frac{N_{ta}\Phi_G}{2\alpha N_d} \left[ 1 - \exp\left( \frac{\alpha}{\Phi_G} \right) \right] \exp\left( \frac{\varphi_s}{\Phi_G} \right) + 1 \right\}. \quad (16)$$

Normalizing (16) yields

$$v_G - v_s + C = \beta \exp(v_s) \quad (17)$$

where $v_G = (V_{gs} - V_{fb})/\Phi_G$, $v_s = \varphi_s/\Phi_G$, $C = \sqrt{\frac{2q\varepsilon_{si}\alpha N_d}{C_{OX}}} = \frac{qN_d t_{film}}{2C_{OX}\varepsilon_{si}}$, and $\beta = -\frac{qN_d t_{film}}{2C_{OX}\varepsilon_{si}} [1 - \exp(\frac{\varphi_s}{\Phi_G})]$. 

Multiplying $\exp(v_G - v_s + C)$ in both sides of (17), it can be re-expressed as

$$(v_G - v_s + C) \exp(v_G - v_s + C) = \beta \exp(v_G + C). \quad (18)$$

Apparently, the normalized surface potential in (18) can be solved explicitly by making use of the Lambert $W$ function, i.e.,

$$v_s = v_G + C - W_0[\beta \exp(v_G + C)]. \quad (19)$$

As a result, the surface potential in the FD mode (i.e., $\varphi_s^f$) is given by

$$\varphi_s^f = v_s \Phi_G. \quad (20)$$

D. Combining the models

In addition, for a complete modeling, we have to model $\varphi_0$. In the subthreshold region, once surface potential is given by (20), $\varphi_0$ can be calculated by using (14). If we make further simplifying assumption that the exponential deep state density can be ignored because of the highly doped polysilicon layer, $\varphi_0$ limited to the subthreshold region (i.e., $\varphi_0^f$) can be solved in the way the same as JL MOSFET, i.e.,

$$\varphi_0^f = V_{gs} - V_{fb} + \alpha \left( 1 + \frac{4\varepsilon_{si}}{C_{OX}t_{si}} \right). \quad (21)$$

In the accumulation region, as we mentioned above, $\varphi_0$ is approximated as $V$. In the transition region between accumulation and subthreshold regions, we rely on a smoothing function for...
description and connection, i.e.,

\[
\varphi_0 = \begin{cases} 
\varphi_f^0, & \varphi_0^f < 0 \\
\frac{\varphi_f^0}{(1 + V_{f0}/V_00)^{m_0}}, & \varphi_0^f \geq 0
\end{cases}
\]  

(22)

where \(m_0\) is a parameter that fits the transition.

The surface potential predicted by (7), (13) and (20) matches well with the numerical solution while giving some errors due to the application of simplifying assumptions during the derivation. In order to improve the accuracy, analogous to our previous studies, corrections based on one-step iterative method can be used. In addition, the transitions between adjacent regions are linked by smoothing functions as required.

III. DERIVATION OF THE DRAIN CURRENT

A special and important case in JL devices is the hybrid channel.5, 7 It means that a part of the channel is in accumulation, i.e., from the source to some flatband position (A point) along the channel, and the rest is in partially depletion, i.e., from the flatband coordinate (A point) up to the drain node. If \(A \leq 0\), no accumulation layer is created, if \(A = L\), the whole channel is accumulated, and if \(0 < A < L\), the current flows in hybrid channel. In other words, if \(V_{gs} \geq V_{fb} + V_{ds}\), the whole channel of the JL TFTs is in the accumulation mode. If \(V_{fb} < V_{gs} < V_{fb} + V_{ds}\), the device is in hybrid channel. If \(V_{fb} < V_{gs} \leq V_{fb}\), the whole channel is in the PD mode. Finally, if \(V_{gs} \leq V_{th}\), the whole channel is in the FD mode, entering into the subthreshold region.

Thus, for the hybrid channel, the channel can be divided into two parts, and the total current has to be written as the sum of two components, i.e.,

\[
I_{d,0} = I_a + I_p = \frac{qW}{L} \mu_{\text{eff}} \int_0^{V_A} N_i dV + \frac{qW}{L} \mu_{\text{eff}} \int_{V_A}^{V_{ds}} N_i dV
\]

(23)

where \(W\) is the channel width, \(\mu_{\text{eff}}\) is the effective mobility, \(N_i\) is the induced free charge in the channel, and \(V_A\) is considered as the voltage at the point A which is approximately given by \(V_{fb}\).

To obtain an explicit calculation of the drain current, we use the effective donor density of \(N_{\text{def}}\) to represent the contributions of both the impurity concentration and trap state density, i.e.,

\[
N_{\text{def}} \approx N_d - N_{\text{ta}} e^{-(\varphi_s - V_{\varphi})}.
\]

In the case of accumulation condition, the drain current is approximated by

\[
I_a = \frac{W}{L} \mu_{\text{eff}} \int_0^{V_A} [2C_{\text{OX}}(V_{gs} - V_{fb} - \varphi_s) + qN_{\text{def}} t_{\text{film}}] dV.
\]

(24)

In this case, differentiating (5) with respect to \(\varphi_s\) leads to

\[
\frac{dV}{d\varphi_s} = 1 + \frac{2\phi_i}{V_{gs} - V_{fb} - \varphi_s}.
\]

(25)

Merging (25) into (24) and integrating, we have

\[
I_a = \frac{W}{L} \mu_{\text{eff}} [f(\varphi_{ss}) - f(\varphi_{fb})]
\]

(26)

\[
f(\varphi_s) = -C_{\text{OX}}(V_{gs} - V_{fb} - \varphi_s)^2 + 4C_{\text{OX}}\phi_i \varphi_s + qN_{\text{def}} t_{\text{film}}\phi_s - 2q N_{\text{def}} t_{\text{film}}\phi_i \ln \left[\frac{V_{gs} - V_{fb} - \varphi_s}{V_{gs} - V_{fb} - \varphi_s}\right]
\]

(27)

where \(\varphi_{ss}\) and \(\varphi_{fb}\) are the surface potentials in source and A point, respectively, which are the solutions of (7) with \(V = 0\) and \(V = V_A\), respectively.
FIG. 2. Plot of the channel potentials vs gate voltage. Parameters used for simulation: \( t_{ox} = 8 \text{ nm}, N_d = 1 \times 10^{19} \text{cm}^{-3}, \)
\( V = 0, t_{gsox} = 10 \text{ nm}, g_d = 1 \times 10^{19} \text{cm}^{-3} \text{eV}^{-1}, \text{and } \phi_G = 0.1 \text{ V}. \)

Similarly, in the PD case, we adopt the relation,\(^7\) i.e.,
\[
\frac{dV}{d\phi_s} = 1 - \frac{2(V_{gs} - V_{fb} - \phi_s)}{\kappa} \tag{28}
\]
where \( \kappa = 2q\varepsilon_{si}N_d/C_{OX}^2. \)

As a consequence, the drain current in PD mode becomes
\[
I_p = \frac{W\mu_{eff}}{L} \left[ h(\phi_{sL}) - h(\phi_{fb}) \right] \tag{29}
\]

\[
h(\phi_s) = -C_{OX}(V_{gs} - V_{fb} - \phi_s)^2
+ \frac{4C_{OX}}{3\kappa} (V_{gs} - V_{fb} - \phi_s)^3
+ qN_{def}t_{film}[\phi_s + (V_{gs} - V_{fb} - \phi_s)^2/\kappa] \tag{30}
\]

where \( \phi_{sL} \) is the surface potential in drain end.

If the channel is completely accumulation, we can only use (26) to predict the drain current and \( V_A \) should tend to \( V_{ds}. \) On the other hand, if there is only PD condition, (29) can be used with \( V_A \) equal to the source voltage. Hence, in order to guarantee the expressions are continuous and smooth, we apply a smoothing function\(^{14}\) to link different operation regions, i.e.,
\[
V_A = \frac{V_{ds}}{[1 + a_2 \exp(-a_2(V_{gs} - V_{fb}))]^{1/2}} \tag{31}
\]
where \( a_2 \) determines the smoothness and obtains the best accuracy in the transition regime when it is set to 6.\(^{14}\)
FIG. 3. Plot of the channel potentials vs gate voltage with different $t_{\text{film}}$. Parameters used for simulation are the same as Fig. 2 except for $g_d = 1 \times 10^{20} \text{cm}^{-3} \text{eV}^{-1}$.

FIG. 4. Plot of the channel potentials vs gate voltage with different $t_{\text{ox}}$. Parameters used for simulation are the same as Fig. 2 except for $N_d = 1.1 \times 10^{19} \text{cm}^{-3}$.
In the subthreshold region (i.e., FD case), the drain current is an exponential function of the gate voltage. Consequently, we use the following expression\textsuperscript{15} to describe the total current in all the operation regions, i.e.,

\[
\frac{I_{ds}}{W} = \frac{1}{2} C_{ox} V_{gs} \left( \frac{V_{gs}}{V_{TH}} \right)^{2} \exp\left( \frac{V_{ds}}{V_{TH}} \right)
\]

FIG. 5. Comparison between modeled (curves) and 2D numerical (markers) results with (a) transfer characteristics and (b) output characteristics.
FIG. 6. Comparison of transfer characteristics between modeled (curves) and 2D numerical (markers) results with different $t_{film}$. Other parameters used for simulation are the same as Fig. 5. The inset shows the comparison of threshold voltage between calculation (curves) and extraction from ATLAS (markers).

\[
I_{ds} = (I_a + I_p) \exp \left( \frac{V_{Geff}}{\eta \phi_s} \right) \left[ 1 - \exp \left( -\frac{V_{ds}}{\phi_s} \right) \right]
\]  

(32)

where $\eta$ is an empirical subthreshold ideality factor, and $V_{Geff}$ is the effective gate voltage which combines the current from subthreshold to above-threshold regions and is defined as

\[
V_{Geff} = -\frac{\ln(1 + \exp[a_3(V_{th} - V_{gs})])}{\ln(1 + e^{a_3})}.
\]

(33)

Herein, the variable $a_3$ can be set to 3. Therefore, when $V_{gs} \gg V_{th}$, $V_{Geff}$ tends to be zero and $I_{ds}$ is determined by $I_a + I_p$. On the other hand, when $V_{gs} \ll V_{th}$, $V_{Geff}$ is approximated by $V_{gs} - V_{th}$, and $I_{ds}$ varies exponentially with $V_{gs} - V_{th}$.

IV. MODEL VERIFICATION AND DISCUSSION

To verify the proposed model, comparisons between the numerical results of (1)-(4) and our proposed solution are shown in Figs. 2–4. It can be clearly seen from Fig. 2 that, the explicit result matches perfectly well with the exact numerical one over a wide range of operation regions. When $V_{gs} > V_{fb}$, the energy band bends down near the surfaces ($\phi_s > 0$), and thus the devices enter into accumulation region. Besides, $\phi_0$ is approaching zero. When $V_{gs} < V_{fb}$, the energy band bends up. Limited to $V_{th} < V_{gs} < V_{fb}$, i.e., PD mode, $\phi_0$ is in the vicinity of zero. While in the FD mode, viz, $V_{gs} < V_{th}$, both $\phi_0$ and $\phi_s$ vary with gate voltage sharply.

The behaviors of $\phi_0$ and $\phi_s$ as a function of gate bias with various film thicknesses and oxide thicknesses are shown in Figs. 3 and 4, as well as the comparisons with numerical results. The film thickness and oxide thickness have a strong impact on the characteristics in the subthreshold region, while they weakly influence the accumulation and PD cases due to the screen of the electric field. Moreover, according to the threshold voltage expression mentioned before, both $I_{film}$ and
FIG. 7. Comparison between modeled results (curves) and experimental data (markers) with (a) transfer characteristics and (b) output characteristics. Parameters used for simulation: $t_{ox} = 17$ nm, $N_d = 1 \times 10^{19} \text{cm}^{-3}$, $t_{film} = 2$ nm, $g_d = 1 \times 10^{15} \text{cm}^{-2} \text{eV}^{-1}$, $\phi_0 = 0.1 \text{V}$, $\mu_0 = 0.26 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, $\chi = 0.055 \text{V}^{-2}$, and $\eta = 3$.

$t_{ox}$ are the relative dominant terms. As a result, $V_{th}$ shifts as $t_{film}$ or $t_{ox}$ changes. Furthermore, in the subthreshold region of Fig. 3, as $t_{film}$ decreases, $\phi_0 - \phi_s$ becomes smaller because of the fully depletion approximation in (14).

To validate the model, drain current modeling is confronted to ATLAS simulations. The following parameters are chosen for ATLAS 2D simulation in Figs. 5 and 6: $L = 10 \mu\text{m}$, $t_{ox} = 7$ nm,
$N_d = 1 \times 10^{19} \text{cm}^{-3}$, $g_d = 2 \times 10^{19} \text{cm}^{-1} \text{eV}^{-1}$, $\phi_G = 0.1 \text{ V}$, and $\mu_{\text{eff}} = 30 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ which is setting as a constant. The fitting parameter $\eta$ used for the proposed model is chosen as $\eta = 3$. From Figs. 5(a) and 5(b), we can see that the modeling characteristics of the long-channel device with $t_{\text{film}} = 10 \text{ nm}$, are fairly good in predicting the results of 2D numerical simulation solved by ATLAS. In Fig. 6, when $t_{\text{film}}$ is decreased to 6 nm, the subthreshold characteristics move towards positive gate voltage, which is coincident with the behavior of surface potential varied with $t_{\text{film}}$, in Fig. 3. In addition, since threshold voltage $V_{\text{th}}$ is a key parameter, when $t_{\text{film}}$ varies, we compare the calculation result of $V_{\text{th}}$ with the extraction from ATLAS, which is shown in the inset. It is clearly seen that the film thickness has a strong impact on the threshold voltage. Moreover, a good prediction is obtained.

To further validate our calculation model, we have compared our solution directly with experimental data. The cross-section of channel with 2-nm-thick nano-belt structure can be approximately modeled by the double-gate structure. In addition, the gate length ($L$) of the device is 1 $\mu$m. From Fig. 7, it is clear that the calculated results are in good agreement with the measured ones in the sub- and above-threshold regions. Moreover, in Fig. 7(b), since the junctionless structure is used, kink effect significant in conventional IM poly-Si TFTs is absent, which occurs when electrical field near the drain is high enough. Furthermore, the increment in the saturation current is decreased as gate voltage is increased. This behavior can be explained by the surface scattering at higher gate bias. As a result, the effective mobility is expressed as $\mu_{\text{eff}} = \mu_0/(1 + \chi V_s^2)$, where $\mu_0$ is the maximum mobility and $\chi$ is the scattering factor.

V. CONCLUSION

This paper presents a closed-form compact model to describe the behavior of the potentials at the surface and at the center of the doped polysilicon layer in JL SDG poly-Si TFTs. The calculation of surface potential as a function of gate voltage in different operation modes is done without the need to solve any transcendental equation or introduce adjusting parameters. The solution of surface potential is validated using a rigorous numerical simulation and obtaining an excellent agreement between them. Prediction of the drain current model based on surface potential is also validated with ATLAS simulation and experimental data. The expression presented here can be applied directly for modeling current for JL SDG poly-Si TFTs in a wide range operation regions.

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