A Turn-On DC Surface-Potential-Based Drain Current Model for Fully-Depleted Poly-Si Thin Film Transistors

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ABSTRACT

A turn-on DC surface-potential-based drain current model for fully-depleted polycrystalline silicon thin film transistors is developed based on the charge sheet model considering both deep and tail acceptor trap states in the grain boundary and the effect of the back surface potential. By integrating the electron concentration, vertically to the polycrystalline silicon/oxide interface, along the inversion layer and using the average electric filed concept, the areal density of the inversion charge with the channel potential is deduced to calculate both the diffusion and the drift components. For the purpose of simplifying the process of the solution, the trapezoidal rule is used to avoid numerical integration in the drift current calculation. In order to further improve the calculation precision in the region where the whole channel is not completely strong inverted, the triangular method is adopted under certain mathematical constraints to replace the usage of the trapezoidal rule in the drift current calculation. Finally, a turn-on DC surface-potential-based drain current model is proposed for FD poly-Si TFTs including both deep and tail acceptor trap states in the GB.

Keywords: model, drain current, surface-potential-based, turn-on, DC, fully-depleted, poly-Si, thin film transistors

1 INTRODUCTION

With devices’ feature sizes scaling down, fully-depleted (FD) silicon-on-insulator (SOI) devices are superior to the traditional bulk MOSFETs in their electric performance, as is also reasonable under the reliability issue concerned [1]. Therefore, FD polycrystalline silicon thin film transistors (poly-Si TFTs) are very suitable for their application.

Characteristics of FD poly-Si TFTs are greatly influenced by both deep and tail trap states in the grain boundary (GB) [2]. Meanwhile, the surface-potential-based modeling strategy [3, 4] originating from the Pao-Sah model [5] takes the lead position in compact MOSFET modeling. Charge sheet model [6, 7] considering both drift and diffusion components with the merit of its simplication and convenience for calculation is widely adopted in device modeling. Since the areal density of injection charge for later both diffusion and drift currents calculation is calculated by integrating the electron concentration along the inversion layer in this paper, it usually brings the numerical integration in later the drift current calculation although the average electric field concept [8] is used. In order to simplify the solution, the trapezoidal rule is used in drift current calculation. For further improving the calculation precision in the region where the whole channel is not completely strong inverted, the triangular method is adopted under certain mathematical constraints to replace the usage of the trapezoidal rule in the drift current calculation. Finally, a turn-on DC surface-potential-based drain current model is proposed for FD poly-Si TFTs including both deep and tail acceptor trap states in the GB.

2 MODEL DERIVATION

In figure 1, the n-type FD poly-Si TFT with the channel length \( L \) and the channel width \( W \) is illustrated. It is assumed with the very thick insulator substrate. The \( z \) direction is perpendicular to the poly-Si/oxide front interface where \( z = 0 \). The \( y \) direction is along the channel where \( y=0 \) at the source end and \( y=L \) at the drain end.

![Figure 1: The schematic structure of FD poly-Si TFTs, defining \( z=0 \) at the poly-Si/oxide front interface, \( y=0 \) at the source end and \( y=L \) at the drain end.](image)

Finally, a turn-on DC surface-potential-based drain current model is proposed for FD poly-Si TFTs including both deep and tail acceptor trap states in the GB.


\[
d\psi/dz = d(F_v^2)/2d\psi \quad \text{of electrostatic potential } \psi \quad \text{and the vertical field in poly-Si layer } F_v \quad \text{and applying Gauss’s law for the front poly-Si/oxide interface, the front and back surface potential equation is obtained as [8]}
\]

\[
\psi_{sf} = V_g - V_{fb} - \frac{1}{C_{ox}} \left(2q\varepsilon_{si}\{N_{Aa} (\psi_{sf} - \psi_{sb}) + N_{Aa} \left[\frac{V_c - 2\phi_f}{\phi_i} \right] \exp\left(\frac{\psi_{sf} - \psi_{sb}}{\phi_i} \right) - \frac{V_c - 2\phi_f}{2\phi_i} \right) \right)
\]

\[
+ N_{deep} \left(\frac{KT_d}{q}\right) \exp\left(-\frac{\psi_{sb} - \phi_f - V_c - \frac{E_g}{2q}}{\phi_i} \right) + N_{tail} \left[\frac{\psi_{sf} - \phi_f - V_c - \frac{E_g}{2q}}{\phi_i} \right] \right] \right) \right)^{1/2}
\]

(1)

where \(\psi_{sf}\) is the front surface potential, \(\psi_{sb}\) is the back surface potential, \(V_g\) is the gate voltage, \(V_{fb}\) is the flat band voltage, \(C_{ox}\) is the gate oxide capacitance per unit area, \(q\) is the electron charge, \(\varepsilon_{si}\) is the silicon permittivity, \(N_{Aa}\) is the active acceptor concentration, \(\phi_i\) is the thermal voltage, \(V_c\) is the channel potential, \(\phi_f\) is the bulk Fermi potential, \(K\) is the Boltzmann constant, \(T_d\) and \(T_i\) are the characteristic temperatures of the deep and tail states, \(N_{deep} = g_d \frac{K\pi T}{\sin(\pi T/T_d)}\) where \(g_d\) is the deep state density at the conduction band edge and \(T\) is the absolute temperature, \(\alpha = \frac{4}{15} \left(\frac{T}{T_i}\right)^2 + \frac{T}{T_i} + \frac{1}{15}\),

\[N_{tail} = g_t K T_i \left[\frac{2\pi - 4}{3} \left(\frac{T}{T_i}\right)^2 + \frac{(6 - 2\pi) T}{T_i} + \frac{4\pi - 8}{3}\right]\]

where \(g_t\) is the tail state density at the conduction band edge and \(E_g\) is the band gap.

Using the assumption of the potential distributed along the vertical direction in poly-Si layer as \(\psi = \psi_{sf} + \psi_{sb} - \psi_{sf}z\) and taking account of the contribution of the active acceptor, the electron and the trapped charge of deep and tail states, the coupling effect of the front and back surface potentials is deduced as [8]

\[
\psi_{sb} = \psi_{sf} - \frac{q}{2\varepsilon_{sf}} N_{Aa} \cdot t_{si} - \frac{q}{\varepsilon_{si}} \frac{t_{si}}{(\psi_{sb} - \psi_{sf})^2}
\]

\[
\{N_{f} \psi_{sf}^2 \exp\left(\frac{\psi_{sf}}{\phi_i}\right) - \exp\left(\frac{\psi_{sb}}{\phi_i}\right)\} + N_{s} \left(\frac{KT_d}{q}\right) \exp\left(\frac{\psi_{sb} - \psi_{sf}}{\phi_i}\right)
\]

\[
+ N_{t} \left(\exp\left(\frac{\alpha \psi_{sf}}{\phi_i}\right) - \exp\left(\frac{\alpha \psi_{sb}}{\phi_i}\right)\right)
\]

(2)

where \(N_1 = N_{Aa} \cdot \exp\left(\frac{V_c - 2\phi_f}{\phi_i}\right)\), \(N_2 = N_{deep} \exp\left(\frac{-\phi_f - V_c - E_g}{2q}\right)\), and \(N_3 = N_{tail} \exp\left(\frac{\alpha \psi_{sf}}{\phi_i}\right)\).

And \(\psi_{sf}\) can be calculated by (1) and (2).

For FD devices with the very thick insulator substrate, \(F_v\) is replaced by the average electric field \(\frac{F_{s_{vf}}}{2}\) where \(F_{s_{vf}}\) is the electric field at the front surface. And integrating the electron concentration along the \(z\) direction in the inversion layer and considering the effect of channel potential in the potential of the inversion layer’s ending point, the areal density of the inversion charge is deduced as [8]

\[
Q_i = \frac{2q n_i \phi_i}{F_{s_{vf}}} \left[1 - \exp\left(\frac{\psi_{sf} - V_c - \phi_f}{\phi_i}\right)\right]
\]

(3)

where \(n_i\) is the intrinsic carrier concentration.

Substituting \(F_{s_{vf}}\) expression obtained by using Gauss’s law for the front poly-Si/oxide interface into (3), \(Q_i\) can be rewritten as

\[
Q_i = \frac{2\varepsilon_{si} q n_i \phi_i}{C_{ox} (V_{g} - V_{fb} - \psi_{sf})} \left[1 - \exp\left(\frac{\psi_{sf} - V_c - \phi_f}{\phi_i}\right)\right]
\]

(4).
According to charge sheet model \([6,7]\),
\[ I_{\text{diffusion}} = W \phi_s \mu_s \frac{dQ}{dy}, \quad I_{\text{drift}} = -\mu_s Q_s W \frac{d\psi_{\text{sf}}}{dy} \]
where \(\mu_s\) is the surface mobility assumed to be constant.

So the diffusion and drift components can be expressed separately as
\[ I_{\text{diffusion}} = \frac{2W\phi_s^2\mu_s qn_s e_{\text{si}}}{L} \left\{ -\exp[\psi_{\text{sf}}(L) - V_d - \phi_f0] + 1 \right\} \]
\[ -\exp[\psi_{\text{sf}}(0) - \phi_f0] + 1 \]
\[ \times \frac{C_{\alpha}}{C_{\alpha}[V_g - V_{fb} - \psi_{\text{sf}}(L) - 1]} \]
where \(V_d\) is the drain bias, and
\[ I_{\text{drift}} = \frac{2W\mu_s qn_s \phi_f}{L} \int_{\psi_{\text{sf}}(0)}^{\psi_{\text{sf}}(L)} \frac{\exp[\psi_{\text{sf}}(L) - V_c - \phi_f0]}{\phi_f} d\psi_{\text{sf}} \] (5)

This drift current (6) usually should be calculated by numerical integration.

For the purpose of simplifying the solution process of (6), the integral
\[ \int_{\psi_{\text{sf}}(0)}^{\psi_{\text{sf}}(L)} \frac{\exp[\psi_{\text{sf}}(L) - V_c - \phi_f0]}{\phi_f} d\psi_{\text{sf}} \] (7)
can be calculated in the following way.

When the points of channel are weak inverted, the front surface potential almost does not change at the different point of the channel. In other words, the corresponding front surface potential interval is very small. Meanwhile, the exponential term of (7) is very large when the points of channel are strong inverted. Therefore, compared with the value of the integrand of (7), the corresponding front surface potential interval is also very small. Therefore, the linear interpolating function can be used in \([\psi_{\text{sf}}(0), \psi_{\text{sf}}(L)]\) to calculate the value of the integral.

Defining \(F(\psi_{\text{sf}}, V_c) = \frac{\exp[\psi_{\text{sf}}(L) - V_c - \phi_f0]}{\phi_f} \) and applying the trapezoidal rule in calculating (7), (7) turns into
\[ I_{\text{drift}} = \frac{2W\mu_s qn_s \phi_f}{L} \left\{ F[\psi_{\text{sf}}(0),0] + F[\psi_{\text{sf}}(L),V_d] \right\} \] (8)
\[ {\psi_{\text{sf}}(L) - \psi_{\text{sf}}(0)} \]

\[ = \frac{2}{L} \int_{\psi_{\text{sf}}(0)}^{\psi_{\text{sf}}(L)} \exp[\psi_{\text{sf}}(L) - V_c - \phi_f0] d\psi_{\text{sf}} \] (9)

\[ \text{and} \]
\[ = \frac{2}{L} \int_{\psi_{\text{sf}}(0)}^{\psi_{\text{sf}}(L)} \exp[\psi_{\text{sf}}(L) - V_c - \phi_f0] d\psi_{\text{sf}} \] (10)

From (5), (8) and (11), the drain current can be expressed as
\[ I = \begin{cases} I_{\text{diffusion}} + I_{\text{drift}_{\text{tri}}}, & \text{satisfying (9) and (10)} \\ I_{\text{diffusion}} + I_{\text{drift}_{\text{tra}}}, & \text{else} \end{cases} \] (12)

Therefore, the turn-on DC surface-potential-based drain current can be calculated from (1), (2) and (12).

## 3 Result and Discussion

For n-type FD poly-Si TFTs with the very thick insulator substrate, including both deep and tail acceptor trap states in GBs, the above proposed turn-on surface-potential-based drain current model is compared with the simulation results of the two-dimensional-device simulator MEDICI \([13]\) from the transfer characteristics of both low and high state densities. The devices’ parameters used in the model are shown in table 1.

Figure 2 and figure 3 show transfer characteristics of device with the low and high state densities under different drain biases, respectively. In figure 2, for the low state density \(g_d = 1.5 \times 10^{18} \text{cm}^{-3} \text{eV}^{-1}\) and \(g_t = 7.5 \times 10^{18} \text{cm}^{-3} \text{eV}^{-1}\), the gate voltage ranges from 0.6 V to 20 V. In figure 3, for
the high state density $g_d = 3 \times 10^{19} \text{ cm}^{-3} \text{eV}^{-1}$ and $g_t = 1.5 \times 10^{20} \text{ cm}^{-3} \text{eV}^{-1}$. The gate voltage varies from 0.9 V to 20 V. In both figures, the drain current model (12) matches the 2D-device simulation under $V_d = 0.1$ V, 1 V and 5 V.

### 4 CONCLUSION

For FD poly-Si TFTs including both deep and tail acceptor trap states in GBs, a turn-on DC surface-potential-based drain current model is developed based on the charge sheet model. The coupling effect of the front and the back surface potentials is deduced considering the contributions of active acceptors, electrons and trapped charges. By using the average electric field concept and considering the effect of the channel potential in the potential of the inversion layer’s ending point, the areal density of the inversion charge is derived to calculate both the diffusion and the drift components. With the merit of simplifying the process of the solution, the trapezoidal rule is used to avoid numerical integration in the drift current calculation. For further improving calculation precision in the region where the whole channel is not completely strong inverted, the triangular method is adopted under certain mathematical constraints to replace the usage of the trapezoidal rule in the drift current calculation. This proposed surface-potential-based drain current agrees with the 2D-device simulation from different transfer characteristics under low and high state densities respectively.

### REFERENCES


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$N_{ac}$</td>
<td>active acceptor concentration</td>
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<tr>
<td>$g_d$</td>
<td>deep state density at the conduction band edge</td>
<td>$1.5 \times 10^{18}$ cm$^{-3}$eV$^{-1}$ (for low state density) $3 \times 10^{19}$ cm$^{-3}$eV$^{-1}$ (for high state density)</td>
</tr>
<tr>
<td>$g_t$</td>
<td>tail state density at the conduction band edge</td>
<td>$7.5 \times 10^{18}$ cm$^{-3}$eV$^{-1}$ (for low state density) $1.5 \times 10^{20}$ cm$^{-3}$eV$^{-1}$ (for high state density)</td>
</tr>
<tr>
<td>$T_d$</td>
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</tr>
<tr>
<td>$T_t$</td>
<td>characteristic temperature of the tail states</td>
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<tr>
<td>$T$</td>
<td>absolute temperature</td>
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</tr>
<tr>
<td>$L$</td>
<td>length of the channel</td>
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Table 1: Values of parameters used in the model.

Figure 2: Transfer characteristics of device with low state density under different drain biases via the drain current model (12) and the 2D-device simulation.

Figure 3: Transfer characteristics of device with high state density under different drain biases via the drain current model (12) and the 2D-device simulation.