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# Quasi-Two-Dimensional Subthreshold Current Model for Polysilicon Thin Film Transistors

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**Abstract:** Based on the diffusion and thermal emission processes, an analytical subthreshold current model for polysilicon thin film transistors (poly-Si TFTs) is developed by a quasi-two-dimensional solution. An analytical expression of the subthreshold swing is subsequently obtained from the surface potential equation and the subthreshold current expression, which takes into account the grain size and trap states. This model has a simple functional form and it can reduce to that of the conventional long channel MOSFET in the case of large grain size and low trap states. The model has been verified by a good agreement between simulated results and experimental data.

**Key words:** polysilicon thin-film transistors; subthreshold; quasi-two-dimensional

## 多晶硅薄膜晶体管亚阈值区准二维模型

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**摘 要:**从准二维泊松方程出发,结合多晶硅扩散和热发射载流子输运理论,建立了多晶硅薄膜晶体管亚阈值电流模型。由表面势方程及亚阈值电流方程求得包含陷阱态和晶粒尺寸的亚阈值斜率解析表达式。模型具有简明的表达式,并且在大晶粒和低陷阱态情形下可简化为传统长沟道 MOSFET 亚阈值区模型。仿真结果与试验数据符合得很好,验证了模型的正确性。

**关 键 词:**多晶硅薄膜晶体管; 亚阈值; 准二维  
**中国分类号:** TN321<sup>+</sup>.5      **文献标识码:** A

### 1 Introduction

Polysilicon thin film transistors (poly-Si TFTs) can be used not only as pixel transistors in the active matrix liquid crystal display (AMLCD) or active matrix organic light emitting diode display (AMOLED) but also for the integration

of the driving circuitry on the same substrate. It is essential to develop a compact model of poly-Si TFTs for circuit design and simulations due to its growing importance in integrated circuits<sup>[1]</sup>. There are only a few quasi-2D models for the above-threshold characteristics of poly-Si TFTs<sup>[2-3]</sup>. In the present work, a quasi-two-dimensional

analytical model for the subthreshold characteristics of poly-Si TFTs is proposed.

## 2 Subthreshold Model

As shown in Fig. 1, it is assumed that the induced electrons by a positive gate bias are fully trapped into the grain boundary when poly-Si TFTs work at the subthreshold region. Thus, the lateral depletion width around the grain boundary is equal to the half of the grain size ( $L_g/2$ ). Based on a quasi-2D solution, the surface electrostatic potential along the channel can be expressed [4]:

$$\psi(0,y) = V^0 - (V^0 - \psi_{ss})\cosh(Ky) \quad (1)$$

with  $V^0 = V_{gf} - \gamma \sqrt{\psi_{ss}}$   
The meanings and the expressions of the symbols can be seen from Ref. [4].

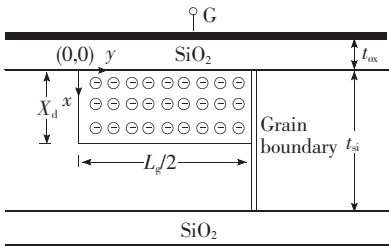


Fig. 1 Cross-section of a n-channel poly-Si TFT at the subthreshold region

Therefore, the surface electrostatic potential at the grain boundary can be expressed as

$$\psi_{gb0} = \psi(0, L_g/2) = V^0 - (V^0 - \psi_{ss})\cosh(KL_g/2) \quad (2)$$

Applying Gauss's theorem to the grain boundary, the total charges trapped at the grain boundary can be expressed as:

$$Q_{it} = 2\epsilon_{si} \int_0^{X_d} E(x, L_g/2) dx = C_0 X_d (V^0 - \psi_{ss}) \sinh(KL_g/2) \quad (3)$$

$$\text{with } C_0 = \frac{2\epsilon_{si}K}{3} (\text{F} \cdot \text{cm}^{-2})$$

As seen from Fig. 2 and similar to Ref. [4]:

$$Q_{it} \approx Q_{AD} = C_1 X_d (\psi_{gb0} - V_i) \quad (4)$$

with  $C_1 = N_A^D q^2 / 3 (\text{F} \cdot \text{cm}^{-2})$

From equations (2), (3) and (4), making

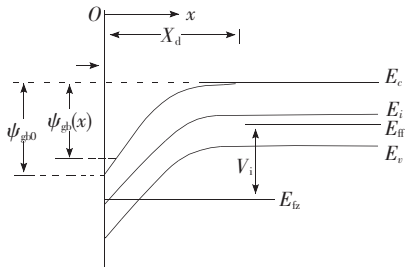


Fig. 2 Energy band diagram at the grain boundary

some algebraic manipulation, yields:

$$\psi_{ss} + f_a \gamma \sqrt{\psi_{ss}} - f_a V_{gf} - (1 - f_a) V_i = 0 \quad (5)$$

with  $f_a = 1 - C_1 / C_2$

$$C_2 = C_0 \sinh(KL_g/2) + C_1 \cosh(KL_g/2)$$

The solution of (5) can be easily obtained:

$$\psi_{ss} = \left[ \frac{-f_a \gamma + \sqrt{(f_a \gamma)^2 + 4f_a V_{gf} + 4(1 - f_a) V_i}}{2} \right]^2 \quad (6)$$

In the case of large grain size and low trap states, Eq. (6) will reduce to that of long MOSFET [5]:

$$\psi_{ss} \approx \psi_{ssM} = \left[ \frac{-\gamma + \sqrt{\gamma^2 + 4V_{gf}}}{2} \right]^2 \quad (7)$$

Using Taylor expansion with first-order approximation, we have

$$\psi_{ss} \approx \psi_{ss0} + \delta V_i \quad (8)$$

with

$$\psi_{ss0} = \left[ \frac{-f_a \gamma + \sqrt{(f_a \gamma)^2 + 4f_a V_{gf}}}{2} \right]^2$$
$$\delta = (1 - f_a) \left( 1 - \frac{f_a \gamma}{\sqrt{(f_a \gamma)^2 + 4f_a V_{gf}}} \right)$$

The grain barrier height in the channel can be written as:

$$\psi_b(y) = \psi_{ss} - \psi_{gb0} = f_b (\psi_{ss} - V_i) \quad (9)$$

$$\text{with } f_b = \frac{C_1 [\cosh(KL_g/2) - 1]}{C_2 - C_1}$$

There will be no charges trapped at the grain boundary and the grain boundary barrier disappears when  $V_i$  is not less than  $\psi_{gb0}$  as seen from Eq. (4). Therefore, we have

$$\begin{cases} \psi_{ss} = \psi_{ss0} + \delta V_i & V_i < \psi_{ssM} \\ \psi_{ss} = \psi_{gb0} = \psi_{ssM} & V_i \geq \psi_{ssM} \end{cases} \quad (10)$$

And then the grain barrier height along the channel can be written as:

$$\psi_b(y) = \begin{cases} f_b(\psi_{ss0} + \delta V_i - V_i) & V_i < \psi_{ssM} \\ 0 & V_i \geq \psi_{ssM} \end{cases} \quad (11)$$

Based on the processes of diffusion and thermal emission, the subthreshold current of poly-Si TFTs can be expressed as:

$$I_{\text{sub}} = W V_t u_0 \exp\left[-\frac{\psi_b(y)}{V_t}\right] \frac{dQ_i(y)}{dy} \quad (12)$$

$Q_i(y)$  is the free charge density along the channel<sup>[5]</sup>:

$$Q_i(y) = -\frac{\gamma C_{\text{ox}}}{2\sqrt{\psi_{ss}}} V_t \exp\left(\frac{\psi_{ss} - 2\varphi_f - V_i}{V_t}\right) \quad (13)$$

From Eq. (11) and (13), integrating Eq. (12) from 0 to  $L$ , where  $L$  is the channel length, we have:

$$I_{\text{sub}} = \frac{W u_0 \gamma C_{\text{ox}}}{2L \sqrt{\psi_{ss0}}} \frac{V_t^2}{1 - f_b} \exp\left[\frac{(1 - f_b)\psi_{ss0} - 2\varphi_f}{V_t}\right] \times \left[1 - \exp\left(-\frac{f_c V_{\text{ds}}}{V_t}\right)\right] \quad (14)$$

Compared with the subthreshold model of the conventional long channel MOSFET<sup>[5]</sup>:

$$I_{\text{sub}} = \frac{W u \gamma C_{\text{ox}}}{2L \sqrt{\psi_{ssM}}} V_t^2 \exp\left[\frac{\psi_{ssM} - 2\varphi_f}{V_t}\right] \times \left[1 - \exp\left(-\frac{V_{\text{ds}}}{V_t}\right)\right] \quad (15)$$

The whole subthreshold current of poly-Si TFTs including the kink effect can be expressed as<sup>[6,7]</sup>:

$$I_{\text{sub\_all}} = I_{\text{sub}} + \Delta I_{\text{kink}} = (1 + K_m) I_{\text{sub}} \quad (16)$$

where  $K_m = \left(\frac{L_{\text{kink}}}{L}\right)^{m_i} \frac{V_{\text{ds}}}{A_i} \exp\left(-\frac{B_i}{V_{\text{ds}}}\right)$  is the multiplication factor of the kink effect, and  $L_{\text{kink}}$ ,  $m_i$ ,  $A_i$  and  $B_i$  are the fitting parameters.

The subthreshold swing  $S$  is given by:

$$S = 2.3 \frac{dV_{\text{gs}}/d\psi_{ss}}{d(\ln I_{\text{sub\_all}})/d\psi_{ss}} \quad (17)$$

From Eq. (5) and (14), we have:

$$S \approx 2.3 V_t \frac{\frac{1}{f_a} + \frac{C_d}{C_{\text{ox}}}}{1 - f_b - \frac{2V_t}{\gamma^2} \left(\frac{C_d}{C_{\text{ox}}}\right)^2} \quad (18)$$

Compared with the subthreshold swing of MOSFET<sup>[5]</sup>:

$$S \approx 2.3 V_t \frac{1 + \frac{C_d}{C_{\text{ox}}}}{1 - \frac{2V_t}{\gamma^2} \left(\frac{C_d}{C_{\text{ox}}}\right)^2} \quad (19)$$

It is shown that the subthreshold swing of poly-Si TFTs is larger than that of the crystalline MOSFET since  $f_a$  and  $f_b$  are both smaller than 1.

### 3 Results and Discussion

Fig. 3 shows the subthreshold current characteristics of n-channel poly-Si TFTs at  $V_{\text{ds}} = 0.1, 5.1, 10.1$  V for  $W/L = 50 \mu\text{m}/50 \mu\text{m}$  and  $W/L = 50 \mu\text{m}/6 \mu\text{m}$ <sup>[8]</sup>. It is shown that the subthreshold current of poly-Si TFTs increases with increasing  $V_{\text{ds}}$  due to the kink effect occurring near to the drain region. And the kink effect becomes more pronounced for short channel devices. As shown in Fig. 3, a good agreement between simulated results and experimental data is obtained with the model parameters indicated in Table 1. It should be noted that a same set of parameters are used to fit the data of different  $L$  in our model.

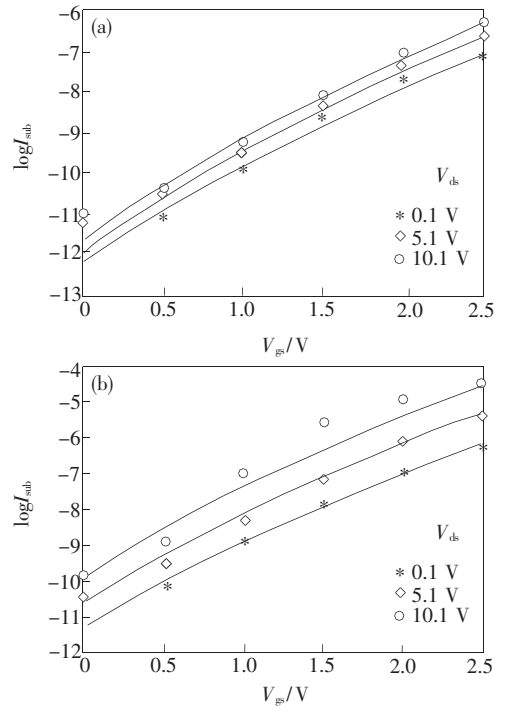


Fig. 3 Experimental data (symbols)<sup>[8]</sup> and simulated results (solid lines). (a)  $W/L = 50 \mu\text{m}/50 \mu\text{m}$ ; (b)  $W/L = 50 \mu\text{m}/6 \mu\text{m}$ .

Table 1 Values of model parameters

| Parameter | Value                                                 | Parameter  | Value                                    |
|-----------|-------------------------------------------------------|------------|------------------------------------------|
| $W$       | $50\times10^{-4}\text{ cm}$                           | $L_g$      | $0.2\times10^{-4}\text{ cm}$             |
| $L$       | $50\times10^{-4}, 6\times10^{-4}\text{ cm}$           | $V_{fb}$   | $-0.15\text{ V}$                         |
| $t_{Si}$  | $100\times10^{-7}\text{ cm}$                          | $\mu_0$    | $60\text{ cm}^2/(\text{V}\cdot\text{s})$ |
| $t_{ox}$  | $100\times10^{-7}\text{ cm}$                          | $L_{kink}$ | $30\times10^{-4}\text{ cm}$              |
| $T$       | $298\text{ K}$                                        | $m_i$      | $1.2$                                    |
| $n_i$     | $1.23\times10^{10}\text{ cm}^{-3}$                    | $A_i$      | $1\text{ V}$                             |
| $N_A^D$   | $1.27\times10^{10}\text{ cm}^{-2}\cdot\text{eV}^{-1}$ | $B_i$      | $14\text{ V}$                            |
| $N_a$     | $1.5\times10^{11}\text{ cm}^{-3}$                     |            |                                          |

4 Conclusion

Based on a quasi-2D Poisson’s equation, an analytical model of subthreshold current of poly-Si TFTs is developed. This model has a simple

functional form and it can reduce to that of the conventional long channel MOSFET in the case of large grain size and low trap states. There is a good agreement between simulated results and experimental data to verify this model.

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