A Physically-Based Analytical Model for a-Si Devices Including Drift and Diffusion Currents

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Abstract

A new compact model for a-Si TFTs is proposed. The model is physically based as the relation between the surface and the quasi-Fermi potentials is correctly accounted for, and therefore implicitly accounts for both linear and saturation operating conditions. Among other consequences, the explicit definition of the threshold and saturation voltages as input parameters is not needed.

1. Introduction

Amorphous Silicon (a-Si) devices like TFTs (Thin-Film Transistors) have met an increasingly higher interest in the last years. In particular, their use in circuit design makes the availability of analytical models particularly attractive. The development of such models is complicated by the presence of a high concentration of trap states in the energy gap of a-Si, which makes it necessary to account for the trap states in every operating region. The energy distribution of the gap states of a-Si, both acceptor-like (g_a) and donor-like (g_d), is accurately modeled by the superposition of two exponential functions, accounting for band-tail states as well as deep states. In the typical operating conditions of n-channel TFTs, the Fermi level is closer to the edge E_C of the conduction band, hence it is placed well within the distribution of acceptor-like states. As a consequence, the influence of the latter on the electric potential and therefore on the drain current becomes dominant. In contrast, the donor-like states, located in the lower half of the gap, are essentially neutral. Dual considerations hold for p-channel transistors. The distribution g_a reads [1]

$$g_a(E) = N_{at} \exp\left(\frac{E - E_C}{k_B T_{at}}\right) + N_{ad} \exp\left(\frac{E - E_C}{k_B T_{ad}}\right), \qquad (1)$$

while g_d is obtained from (1) with $a \leftarrow d$, $E - E_C \leftarrow E_V - E$. In this paper, the analytical theory originally devised for crystalline-silicon MOSFETs [2] has carefully been reworked in order to incorporate the effects of the trapped charge. In the next section the theory is outlined along with the approximations to be introduced, which are discussed with the aid of numerical simulations. The theory is presented for n-channel devices, in which the source and drain diffusions are n^+ doped and the gate bias V_G is such as to create an electron channel. The approach overcomes some limitations of the currently-used analytical models for a-Si devices; its features are compared with experiments in section 3.

2. Theory and Implementation

The charge density of a-Si is expressed by $\varrho = q\,(p + p_d - n - n_a + N)$, where n_a (p_d) is the concentration of electrons (holes) trapped in the acceptor (donor) states:

$$n_a = \int g_a P_a \,\mathrm{d}E\,, \qquad p_d = \int g_d P_d \,\mathrm{d}E\,, \tag{2}$$

in which the integrals extend over the gap. In a non-equilibrium condition, the acceptor-state occupation probability reads

$$P_a = \{\exp\left[(E - E_{F0} - q\varphi + q\xi_a)/(k_B T_L)\right] + 1\}^{-1}\,, \tag{3}$$

where φ is the electrostatic potential (assumed to vanish in the bulk), T_L the lattice temperature, and $E_{F0} - q\xi_a$ the quasi-Fermi level of the trapped electrons. As the material is typically undoped, and the trap density large, the non-degenerate expressions for the free carriers hold; in particular,

$$n = N_C \,\exp\left[(-E_C + E_{F0} + q\varphi - q\xi_n)/(k_B T_L)\right]\,, \tag{4}$$

with $E_{F0} - q\xi_n$ the quasi-Fermi level of the conductions electrons. Similar expressions hold for P_d and p. The value of $E_{F0} - E_C$ is determined by imposing the bulk-neutrality condition $p + p_d = n + n_a$ in equilibrium. The integral providing n_a can be evaluated by splitting the integration interval at $E_{F0} + q\varphi - q\xi_a$ and approximating the occupation probability following [3]; this yields an analytical expression for $n_a(\varphi, \xi_a)$. To proceed, let x be the coordinate normal to the channel and $\mathcal{E}$ the component of the electric field along x (for reference, a schematic cross-section of an inverted-staggered a-Si TFT is reported in Fig. 1). As the channel is formed by electrons, it is $\mathcal{E} > 0$; in addition, the hole concentrations in the charge-density expression are negligible in the channel region, whence $\varrho = -q\,[n(\varphi, \xi_n) + n_a(\varphi, \xi_a)]$. Here ξ_n, ξ_a depend at most on the coordinate y along the channel; as a consequence, Poisson's equation can be integrated analytically in x using the customary gradual-channel-approximation theory:

$$-\varepsilon_{\mathrm{sc}} \frac{\mathrm{d}^2\varphi}{\mathrm{d}x^2} = \varrho \quad \Rightarrow \quad \varepsilon_{\mathrm{sc}} \frac{\mathrm{d}\mathcal{E}^2}{\mathrm{d}x} = 2\,q\,[n(\varphi, \xi_n) + n_a(\varphi, \xi_a)]\,\frac{\mathrm{d}\varphi}{\mathrm{d}x}\,, \tag{5}$$

whence $\mathcal{E} = \mathcal{E}(\varphi, \xi_n, \xi_a)$. Letting φ_s be the surface potential at y, the mobile charge per unit area is

$$Q_i(\varphi_s, \xi_n, \xi_a) = -q \int_0^\infty n \,\mathrm{d}x = -q \int_0^{\varphi_s} (n/\mathcal{E})\,\mathrm{d}\varphi\,. \tag{6}$$

It is worth noting that (6) departs from the customary expression $Q_i = Q_{\mathrm{sc}} - Q_b$ of the monocrystalline doped silicon, in which $Q_b \propto \sqrt{\varphi_s}$.

From the solution of (5) one finds that $\mathcal{E}^2$ is a linear combination of three exponentials, whose exponents are inversely proportional to T_L, T_{at}, and T_{ad}, respectively. It is found that each term of the combination is dominant over the others in a particular subinterval of $[0, \varphi_s]$. Thanks to this, the last integral in (6) can be carried out by, first, splitting the integration domain, and then by neglecting in each subintegral the less relevant terms of the combination. This procedure has also the advantage that each term can be calculated analytically. A comparison with the exact calculation of (6), shown in Fig. 2, indicates that the approximation is satisfactory. It is also worth mentioning that no assumption is made here about the shape of the inverted layer in the x direction, hence the theory which is being worked out here does not lead to a

charge-sheet model.
From the procedure depicted above it is also found that the functional dependence of Q_i on the potentials is of the form $Q_i = Q_i(\varphi_s - \xi_n, \varphi_s - \xi_a)$. A similar calculation yields an analytical expression for the trapped charge per unit area, $Q_a(\varphi_s, \xi_n, \xi_a) = -q \int_0^\infty n_a \, \mathrm{d}x$, such that $Q_a = Q_a(\varphi_s - \xi_n, \varphi_s - \xi_a)$. In turn, the total semiconductor charge per unit area is given by $Q_{\mathrm{sc}} = -C_{\mathrm{ox}}(V_G - V_{FB} - \varphi_s)$, where C_{ox} is the insulator capacitance per unit area and V_{FB} the flat-band voltage. Combining the above with $Q_{\mathrm{sc}} = Q_i + Q_a$ yields $\varphi_s = \varphi_s(\xi_n, \xi_a)$.
Fig. 3 shows, by way of example, the result of a fully-numerical calculation of φ_s, ξ_n, and ξ_a, for a drain voltage V_D corresponding to the saturation regime, in an n-channel TFT fabricated at the CNR-IESS Laboratory. One notices that $\xi_a = \xi_n$, so that the balance relation $Q_{\mathrm{sc}} = Q_i + Q_a$ actually yields $\xi_n = \xi_n(\varphi_s)$, whence $Q_i = Q_i(\varphi_s - \xi_n)$. In conclusion, the mobile charge per unit area Q_i is given by an analytical expression of the argument $\chi = \varphi_s - \xi_n$. Inverting $\xi_n = \xi_n(\varphi_s)$ and using the above leads to $\chi = \chi(\xi_n)$, to be used in the definition of the drain current

$$I_D = -\mu_e \frac{W}{L} \int_{V_S}^{V_D} Q_i(\varphi_s - \xi_n) \, \mathrm{d}\xi_n = -\mu_e \frac{W}{L} \int_{\chi(S)}^{\chi(D)} Q_i(\chi) \frac{\mathrm{d}\xi_n}{\mathrm{d}\chi} \, \mathrm{d}\chi_n \,, \tag{7}$$

with μ_e the average over the channel of the electron mobility μ_n. The definition of χ also yields $Q_{\mathrm{sc}} = -C_{\mathrm{ox}}(V_G - V_{FB} - \chi - \xi_n)$, whence $\mathrm{d}\xi_n/\mathrm{d}\chi = \mathrm{d}Q_{\mathrm{sc}}/\mathrm{d}(C_{\mathrm{ox}}\chi) - 1$. Finally, from $Q_{\mathrm{sc}} = Q_i + Q_a = Q_{\mathrm{sc}}(\chi)$ it follows

$$I_D = \mu_e \frac{W}{L} \int_{\chi(S)}^{\chi(D)} Q_i(\chi) \left[1 - \frac{\mathrm{d}Q_{\mathrm{sc}}(\chi)}{\mathrm{d}C_{\mathrm{ox}}\chi}\right] \mathrm{d}\chi \,. \tag{8}$$

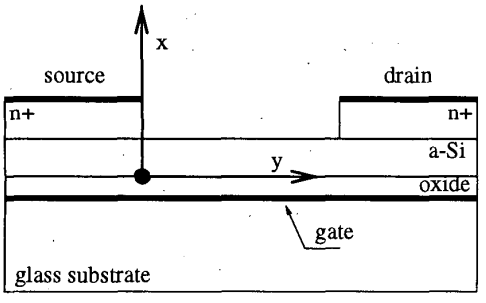

Fig. 1.

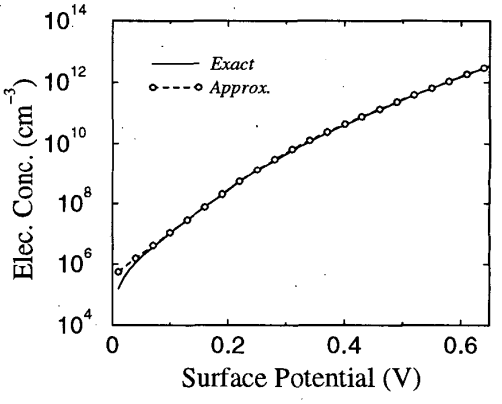

Fig. 2.

3. Results and Conclusions

Eq. (8) constitutes the last step in the calculation of the channel current, and the only one which has to be carried out numerically. In fact, the approximations to be introduced in the integrand and in the integration limits $\chi(S)$, $\chi(D)$ in order to make the calculation analytical, are too heavy to be of practical use. As an application example, Fig. 4 shows the drain current vs. the drain voltage of an a-Si TFT whose structure is reported in [3]. The symbols represent the experimental data while the

continuous lines are the drain current calculated by means of the new model. The transfer characteristics are not reported as the experimental data were not available at the moment of preparing this manuscript; however, comparisons with fully-numerical calculations show that the transfer characteristics are correctly reproduced in both the above- and below-threshold regimes.

To conclude, in this paper a new analytical model for a-Si TFTs has been presented. The model is physically based as the relation between the surface and the quasi-Fermi potentials is correctly accounted for, and therefore implicitly accounts for both linear and saturation operating conditions. Furthermore, it does not require the explicit definition of the threshold and saturation voltages as input parameters, which are rather ambiguously determined in this kind of devices.

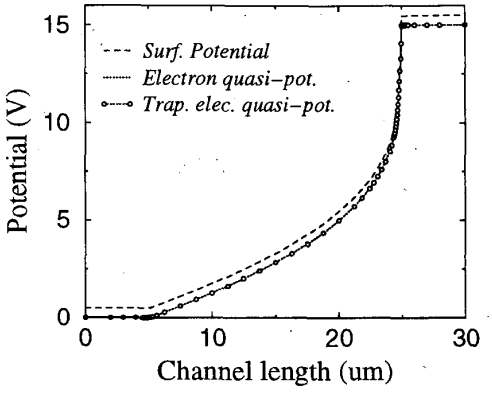

Fig. 3.

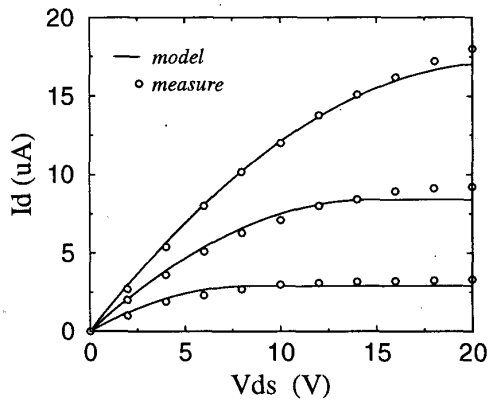

Fig. 4.

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