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All the physical and electrical parameters of the MOS transistor on a single graph (QΨ)*

G. Vincent[a]

Département de Physique, Université Joseph Fourier, Grenoble, France
Laboratoire de Technologie de la Microélectronique, 17 avenue des Martyrs, 38054 Grenoble 9, France

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Abstract. A single and simple graph is proposed, to visualize the impact of all the numerous parameters playing a role in the metal-oxide-semiconductor (MOS) transistor characteristics: doping and permittivity of the semiconductor, thickness, permittivity and charge of the oxide, temperature, and finally gate, drain and substrate voltages. In addition, MOS structure and capacitance properties are presented.

PACS. 85.30.Tv Field effect devices – 85.40.-e Microelectronics: LSI, VLSI, ULSI; integrated circuit fabrication technology – 85.30.De Semiconductor-device characterization, design, and modeling – 73.40.Qv Metal-insulator-semiconductor structures (including semiconductor-to-insulator)

1 Introduction

In order to understand the behaviour of the MOS transistor, as a function of the many parameters which play a role, we need complicated analytical expressions, which do not allow a synthetic view of the influence of each one of these various parameters.

Here we propose a graphical representation of these equations which, as far as we know, is new. It enables us to visualize the influence on the current of the transistor, but also on the potentials and the electric fields, of: – the gate voltage – the drain voltage – the substrate voltage – the thickness of oxide and its permittivity – the doping of the substrate – the oxide charge. The length and the width of the MOST, as well as the effective mobility of the carriers, act as constant factors for the current.

We will first investigate the MOS structure, whose properties will be then used to establish the MOS transistor characteristics.

* This paper is a resume of a lesson (in French) for Electrical Engineering Master's students. The complete text can be found at: `http://perso.wanadoo.fr/physique.belledonne/`.
A simplified version of this paper has been published at: 8[es] journées pédagogiques, CNFM, 2004 dec. 1, edited by O. Bonnaud, H. Lhermite, CCMO, Université de Rennes 1, France.

[a] e-mail: `gilbert.belledonne@wanadoo.fr`

2 MOS structure

2.1 Ideal MOS structure

Let us choose a P type semi-conductor (doping: N_a, permittivity: $\varepsilon_{\mathrm{SC}}$) and start with the traditional expression of the charge per unit of area Q_{SC}^A of the semi-conductor (SC), according to its surface potential ψ_s (cf. for example [1], p. 368). For a P type SC, this space charge per unit area can be reduced to:

$$Q_{SC}^A = \pm\left[2\varepsilon_{sc} q N_a \left\{\frac{kT}{q}\left(e^{-q\psi_s/kT}-1\right)+\psi_s+\frac{kT}{q}e^{q(\psi_s-2\psi_b)/kT}\right\}\right]^{1/2}.$$

Opposite sign of ψ_s — holes — acceptors — electrons

The back side of the SC is assumed to be at potential zero. The potential ψ_b represents, in the neutral material, the potential difference between the intrinsic level and the Fermi level: $\psi_b = (kT/q)\ln(N_a/n_i)$ where n_i is the intrinsic concentration, T the temperature, k the Boltzmann constant, and q the elementary electronic charge.

This function is often represented using log-linear coordinates, but in the case in hand, its meaning will be clearer with a linear representation. In Figure 1, we can make out a $\sqrt{\psi_s}$ variation (depleted zone charge) between two exponential regions: one corresponding to the holes positive charge (accumulation) and the second to the electrons (inversion).

This figure represents the first part of the MOS structure study. Indeed the potential ψ_s is not accessible to

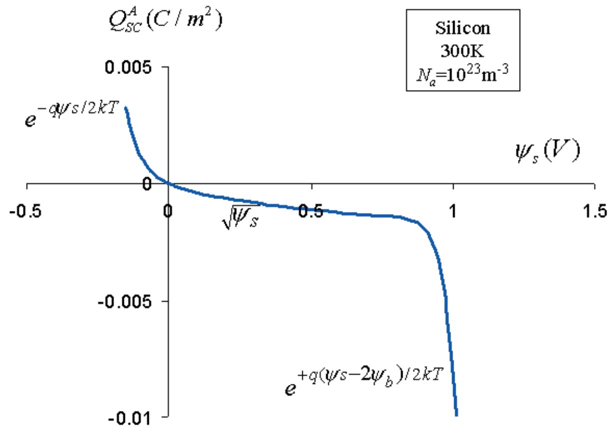

Fig. 1. $Q\Psi$ graph: SC charge per unit area versus surface potential.

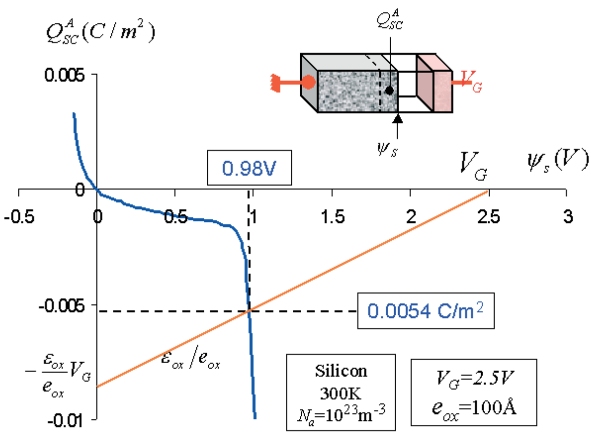

Fig. 2. Graphical solution of SC charge per unit area as a function of gate voltage V_G for an ideal MOS structure.

the operator, who can only modify the gate potential V_G. Neglecting initially the work-function difference and other parameters, such as oxide charge, it is very easy to establish the following relationship:

$$Q^A_{\mathrm{SC}} = \frac{\varepsilon_{ox}}{e_{ox}}(\psi_s - V_G)$$

with e_{ox} and ε_{ox} being the oxide thickness and permittivity. The structure state is thus given by the intersection of this straight line, representing oxide capacitance, with the previous curve (cf. Fig. 2).

In addition this graph enables us to entirely describe the MOS capacitance characteristic using $\left|Q^A_{\mathrm{SC}}/V_G\right|$ to obtain the static capacitance per unit area, and a differential $\left|\delta Q^A_{\mathrm{SC}}/\delta V_G\right|$ for the low frequency measurements.

In order to get tractable expressions, we now need to introduce classical simplifications. From Figure 2, we can observe that in accumulation as well as in inversion, the surface potential ψ_s changes slowly with the gate voltage; therefore, the two exponentials are replaced by verticals, at $\psi_s = 0$ for the holes (accumulation), and at $\psi_s = 2\psi_b$ for the electrons (inversion), values for which the arguments of their exponential become positive. In the inversion situation, the potential ψ_s is then fixed to $2\psi_b$.

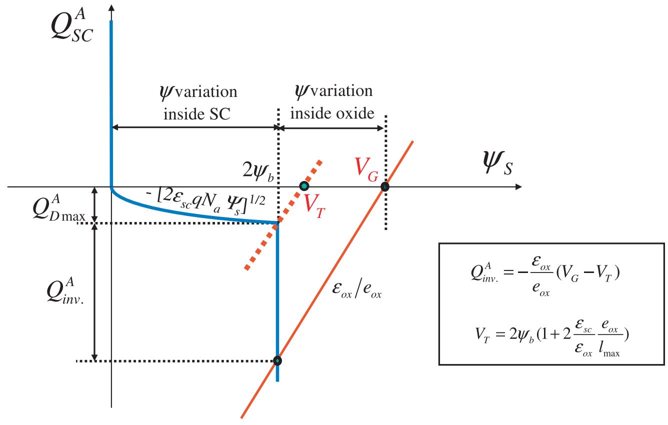

Fig. 3. $Q\Psi V$ graph: informations on ideal MOS structure.

Figure 3 summarizes the main features of the MOS structure ($Q\psi V$ graph). We denote the maximum depleted zone charge by $Q^A_{D\max}$ and the inversion charge by Q^A_{inv} where:

$$Q^A_{inv} = -\frac{\varepsilon_{ox}}{e_{ox}}(V_G - V_T).$$

The threshold voltage V_T, specific value of V_G from which the inversion will be significant, can be expressed using dimensionless ratios:

$$V_T = 2\psi_b\left(1 + 2\frac{\varepsilon_{\mathrm{SC}}}{\varepsilon_{ox}}\frac{e_{ox}}{l_{\max}}\right).$$

The length $l_{\max}$ is the depth of the deserted zone when $\psi_s = 2\psi_b$: $l_{\max} = \sqrt{2\varepsilon_{\mathrm{SC}}(2\psi_b)/qN_a}$.

The depletion charge $Q^A_{D\max}$ increases with doping and therefore Q^A_{inv} decreases. The SC surface potential $2\psi_b$ slightly increases with doping and temperature.

By extension of the $Q\psi V$ graph, the effect of deep depletion, and return to equilibrium following a rapid voltage V_G applied to the gate, are also very easy to understand, as shown in Figure 4: as time increases, the surface potential and the depletion charge decrease, whereas the total charge and inversion charge increase.

2.2 "Non-ideal" MOS structure

A work function difference Φ_{ms}, between the grid and the SC, would shift the straight line of oxide capacitance of $\Delta\psi_s = -\Phi_{ms}$. In the same way, a charge in oxide would shift it by

$$\Delta Q^A_{\mathrm{SC}} = -\frac{x_c}{e_{ox}}Q^A_{ox}$$

where Q^A_{ox} represents the charge per unit area in the oxide, and x_c the barycentre of these charges, measured from metal-oxide interface; as a matter of fact, this explains easily the memories behaviour. The sum of these two effects is the well-known flat band voltage V_{fb}; all the ideal equations become correct using $V_G - V_{fb}$ instead of V_G with:

$$V_{fb} = \Phi_{ms} - \frac{x_c}{\varepsilon_{ox}}Q^A_{ox}.$$

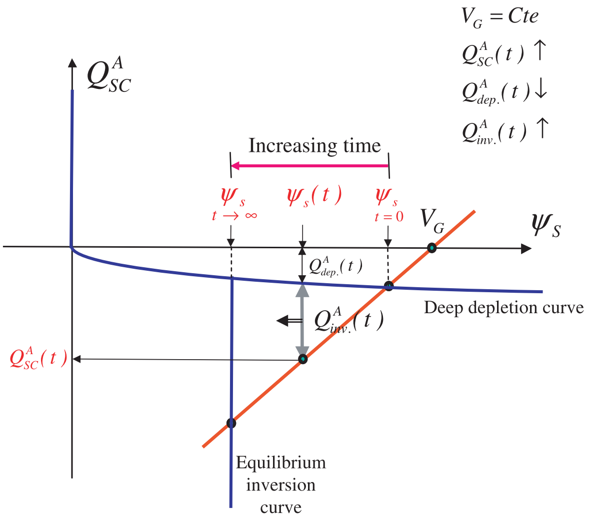

Fig. 4. Generation of inversion charge after deep depletion.

Obviously, V_{fb} can be affected by other parameters like the parasitic interface trapped charge density Q^A_{it}.

3 MOS transistor

3.1 Inversion conditions

What will be the result of the addition of two N type zones, on both sides of the MOS structure: the grounded source, and the V_D biased drain? Here we absolutely have to refer to [1] pages 435–437, and a remarkable approach proposed by [2], who have presented three dimensional graphs of the electrostatic potential $\psi(x, y)$.

On the source side, no significant change occurs: there is no applied potential difference between the source and the P substrate, and therefore accumulation, as depletion and inversion, occur under the same conditions. Thus the previous $Q\psi V$ graph is unchanged on the source side.

On the drain side, there is no change for accumulation and depletion mode: the holes, which accumulate or deplete, are managed by the material P (management of majority carriers). The inversion mode has a completely different behaviour: the drain energy level is going down qV_D and, in order to obtain inversion, it is necessary to shift the surface channel potential of V_D; actually, it is necessary to maintain, locally, the same electronic energy level for the channel and the drain. This represents the management of P semi-conductor minority carriers by a close N material (usual concept of quasi Fermi level). In conclusion, on the $Q\psi V$ graph, we have to move the surface potential of the inversion from $2\psi_b$ to $2\psi_b + V_D$ (cf. in Fig. 5 the $Q\psi V^2$ graph).

This figure shows an inversion charge weaker on the drain side. There are two reasons for this: the electrostatic potential difference between the gate and the substrate is smaller i.e. $V_G - 2\psi_b - V_D$, instead of $V_G - 2\psi_b$ on the source side, and the depleted zone is larger on the drain side.

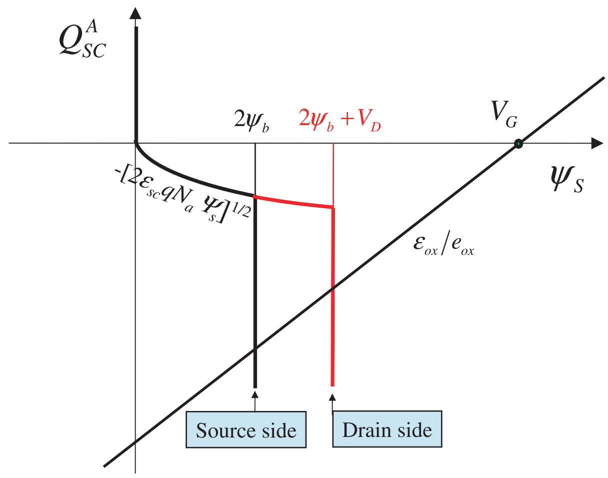

Fig. 5. $Q\Psi V^2$ graph for MOS transistor.

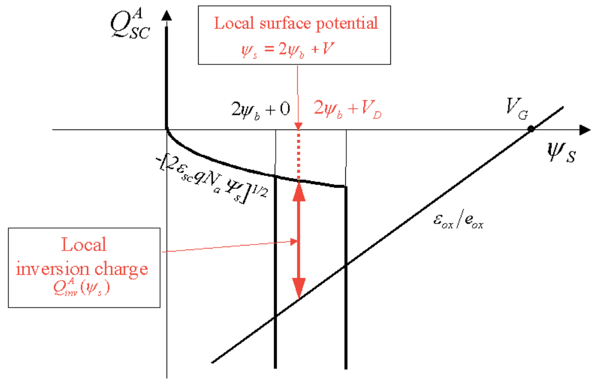

Fig. 6. Local inversion charge versus surface potential.

3.2 Drain source current

In inversion mode, the current is a conduction current, the electrons being carried away by the local electric field $|d\psi_s/dy|$ where y is a space coordinate from the source to the drain. If W is the width of the transistor, the local current relationship is:

$$I = \mu_n W Q^A_{inv} d\psi_s/dy$$

which becomes in the differential form:

$$I dy = \mu_n W Q^A_{inv} d\psi_s.$$

The local inversion charge Q^A_{inv} is clearly shown in Figure 6. The integration from the source to the drain, at distance L, gives:

$$IL = \mu_n W \int_{2\psi_b}^{2\psi_b + V_D} Q^A_{inv}(\psi_s) d\psi_s.$$

The integral in the $Q\psi$ plane is nothing else than the area $A_{Q\psi}$, bounded by the two verticals $2\psi_b$ and $2\psi_b + V_D$, the square root of depletion, and the straight line of oxide

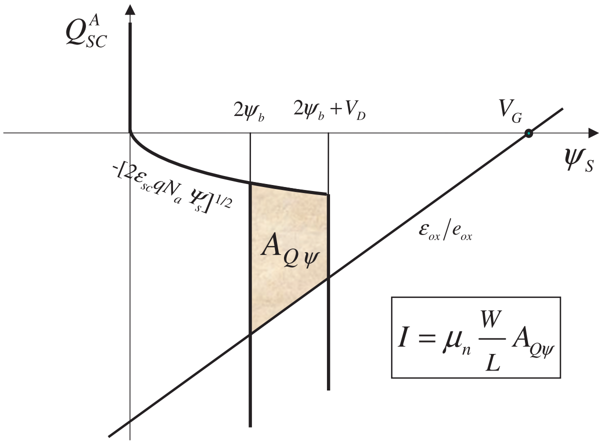

Fig. 7. Drain source current for MOS transistor.

capacitance (cf. Fig. 7). From this we can deduce:

$$I = \mu_n \frac{W}{L} A_{Q\psi}.$$

The $Q\psi V^2$ graph greatly simplifies the discussion of the various MOST operations and characteristic voltage values, that is to say:

– For V_D, the pinch-off voltage which cancels the inversion on the drain side, named saturation voltage V_{Dsat}. Obviously V_G can play a similar role.
– For V_G, the voltage which cancels the inversion near the source, the threshold voltage V_T.

If V_G is lower than V_T, there is only one point of intersection. The surface potential is thus the same at the source side and the drain side, ψ_s is constant along the channel, the electric field is null, and consequently the only possible current is a diffusion current (subthreshold current).

3.3 Substrate bias effect

This representation also easily explains the very astonishing effect which occurs upon application of a substrate bias V_{sub}, negative in order to maintain the source-substrate diode in a reverse state:

– The current decreases whereas in a simple structure MOS, (that is without source-drain), the inversion free carriers of the oxide-SC interface would increase, which should lead "a priori" to an increase in the current.
– The electric field in the oxide remains unchanged.

On the $Q\psi$ graph, the verticals $2\psi_b$ and $2\psi_b + V_D$ which relate to the electrons, managed by the source and the drain, are unchanged. But V_{sub} has a direct effect on the holes population: the accumulation and depletion curves are shifted by V_{sub} (cf. the $Q\psi V^3$ graph in Fig. 8).

The current reduction is clearly highlighted, and it appears that in strong inversion, the potential differences in the oxide, near the source side ($V_G - 2\psi_b$), and drain side ($V_G - 2\psi_b - V_D$), are unchanged; therefore the oxide electric field does not depend on V_{sub}.

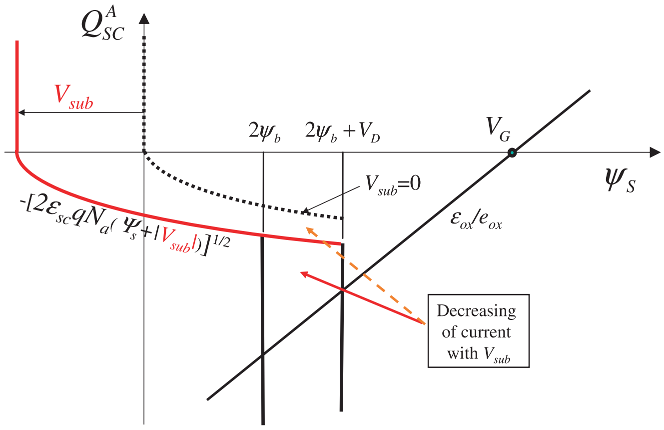

Fig. 8. $Q\Psi V^3$ graph: substrate voltage effect on charges, potentials, and current.

4 Conclusion

Obviously the use of this graphical representation does not imply a qualitative approach. As an example, exploiting the $Q\psi V^3$ graph, we obtain the classical current relationship:

$$I = \mu_n \frac{W}{L} \frac{\varepsilon_{ox}}{e_{ox}} \left[\left(V_G - 2\psi_b - \frac{V_D}{2} \right) V_D - \frac{2}{3} \frac{\sqrt{2\varepsilon_{SC} q N_a}}{\frac{\varepsilon_{ox}}{e_{ox}}} \left\{ (V_D + 2\psi_b + V_{sub})^{\frac{3}{2}} - (2\psi_b + V_{sub})^{\frac{3}{2}} \right\} \right].$$

The benefits of the approach using the $Q\psi V^n$ graph are twofold:

– This graph enables an easy visualisation of the impact of the material and electrical parameters on the MOS and MOST behaviour: think of V_D for example in the above equation. Moreover the physicals reasons for these behaviours are highlighted.
– The relevance of the frequently used approximations, which lead finally to

$$I = \mu_n \frac{W}{L} \frac{\varepsilon_{ox}}{e_{ox}} \left(V_G - V_T - \frac{V_D}{2} \right) V_D, \quad (1)$$

for $V_{sub} = 0$, can be easily evaluated, assuming a constant depletion charge from the source to the drain.

References

1. A.S. Grove, *Physics and technology of semiconductor devices* (Wiley, NY, 1967)
2. S.M. Sze, *Physics of semiconductor devices* (Wiley, NY, 1981)