Sensors and Actuators, *9* (1986) 313 - 321

THRESHOLD VOLTAGE VARIATIONS IN N-CHANNEL MOS TRANSISTORS AND MOSFET-BASED SENSORS DUE TO OPTICAL RADIATION

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(Received November 29 1985, in revised form February 21, 1986, accepted May 15, 1986)

Abstract

The influence of optical radiation on the MOSFET threshold voltage has been investigated theoretically as well as experimentally For conventional MOSFETs the influence is negligible, but for open-gate FET-based sensors, such as the ISFET, optical radiation can cause a considerable threshold voltage shift An explanation of the threshold voltage shift due to illumination is given, based on the analysis of quasi-equilibrium effects in an illuminated semiconductor surface layer The relation between the threshold voltage and the optical radiation intensity has been derived Experimental results are given

1 Introduction

In recent years, there has been a growing interest in the utilization of insulated-gate field-effect transistor structures and related devices as sensors For example, visible and infrared imagers, piezoelectric strain sensors, various chemical sensors, as well as humidity and gas sensors based on these structures have all been reported in the literature

Although there is a vast store of knowledge concerning the effect of optical radiation on the electrophysical parameters of MIS capacitors [1 - 4], no information is available pertaining to the effect of optical radiation on MISFET parameters and characteristics, which is a serious drawback with respect to the application of illuminated MOSFET-based sensors For conventional MISFETs this problem is of minor importance, but for open-gate FET-based sensors it is essential to consider it

For instance, we observed a gate–source voltage shift of approximately 50 mV in ISFETs applied in a source follower concept, due to normal ambient lighting This voltage shift is comparable to that produced by a change of 1 pH unit in a test solution, and indicates the importance of effectively reducing the ISFET light sensitivity

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Recording an $I_d - V_{gs}$ curve, we observed a drain–current shift due to illumination that is caused by two effects drain–bulk diode photocurrent (vertical shift) and threshold voltage shift (horizontal) Measurements have shown that the electron Hall mobility is independent of light up to an intensity of $\sim 100\ \mu W/mm^2$, and therefore we assume the drift mobility is also independent of light The nature of the drain–bulk photocurrent is well known from ordinary photodiodes, therefore our current research efforts have been concentrated on the MOSFET threshold voltage shift as a function of optical radiation

2 Theory

The threshold voltage V_t of an N-channel MOS transistor can be written as follows

$$V_t = \phi_{MS} - \frac{Q_{ss}}{C_{ox}} + 2\phi_F - \frac{Q_B}{C_{ox}} = V_f + 2\phi_F + \frac{+2\sqrt{|\epsilon q N \phi_F|}}{C_{ox}} \tag{1}$$

The symbols used are defined as follows

ϕ_F = Fermi potential,

ϕ_{MS} = metal–semiconductor Fermi potential difference,

Q_{ss} = extrinsic charge due to surface states, interface energy states, oxide traps, etc ,

C_{ox} = gate oxide capacitance per unit area,

Q_B = charge per unit area in the depletion region underneath the surface,

V_f = flat band voltage,

N = impurity concentration,

ϵ = permittivity of the semiconductor

To express this equation as a function of the optical radiation intensity I_{OR}, each of the variables must be written explicitly in terms of I_{OR}

When optical radiation acts on the MOSFET, the equilibrium conditions in a semiconductor are disturbed by light-induced excessive electron–hole pairs The incident light causes a perturbation of the carrier concentrations throughout the semiconductor, producing in turn separate hole and electron quasi-Fermi levels

When describing the phenomena occurring in an illuminated MOSFET, the following simplifying assumptions have been made

(1) The considered structure is assumed to satisfy the conditions of the 'ideal' MOS structure

(2) The bipolar generation occurs uniformly within the whole volume of silicon under the gate

(3) Quasi-Fermi levels are spatially constant and the positions of these levels are fixed by the light-perturbated carrier concentration This assumption is acceptable in the case of weak surface recombination [5]

(4) The metal–semiconductor Fermi potential difference ϕ_{MS} as well as the surface state density Q_{ss} are assumed to be independent of optical radiation

(5) Surface recombination is ignored

(6) The lifetimes of electrons and holes are equal to each other and constant over the whole volume and surface layer of the semiconductor

(7) Optically stimulated charge exchange with surface states as well as photoemission to the dielectric are neglected

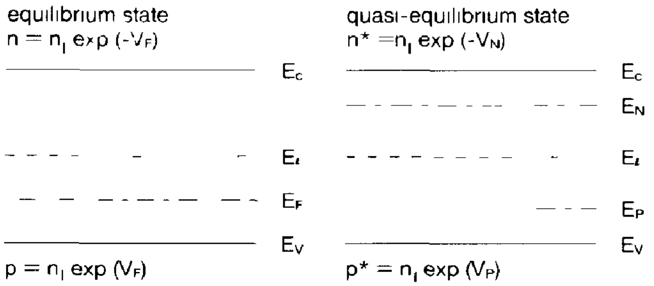

Fig 1 Energy diagrams of a semiconductor for equilibrium and quasi-equilibrium states E_V = energy of valence band edge, E_C = energy of conduction band edge, E_i = energy of the middle forbidden gap, E_F = energy of the Fermi level, E_N = energy of the electron quasi-Fermi level, E_P = energy of the hole quasi-Fermi level

The energy diagrams of a semiconductor are now considered (Fig 1) The thermodynamic equilibrium condition

$$np = n_i \exp(-V_F) n_i \exp(V_F) \tag{2}$$

with V_F the normalized Fermi potential ($V_F = \phi_F q/kT$) and n_i the instrinsic concentration, is disturbed by optical radiation producing separate hole and electron quasi-Fermi levels In the normalized form these are respectively denoted as V_P and V_N, and can be written as

$$V_N = -\frac{E_N - E_i}{kT} \tag{3}$$

$$V_P = -\frac{E_P - E_i}{kT} \tag{4}$$

For a low light generation level it is possible to assume that the temperature and energy of the crystal do not change This state is the so called quasi-equilibrium state The total electron and hole quasi-equilibrium concentrations can then be described by the following equations

$$n^* = n + \Delta n \tag{5}$$

$$p^* = p + \Delta p \tag{6}$$

where n^* and p^* are the electron and hole quasi-equilibrium concentrations, respectively (all quantities for quasi-equilibrium states will be signified by asterisks)

The product of the electron and hole concentrations for the quasi-equilibrium state differs from that for the equilibrium state

$$n^*p^* = n_i \exp(-V_N) n_i \exp(V_P) = n_i^2 \exp(V_P - V_N) \tag{7}$$

The distance between the quasi-Fermi levels V_P and V_N characterizes the deviation from the equilibrium state

The product of n^* and p^* can now also be written as

$$n^*p^* = n_i^{*2} \tag{8}$$

where n_i^* is equivalent to the value of n_i under illuminated conditions, which we will call the effective intrinsic concentration

It can be shown that the description of surface region parameters in the quasi-equilibrium state can be presented analogously to that of the equilibrium state, replacing the instrinsic concentration n_i by the effective instrinsic concentration n_i^* and the normalized Fermi potential $V_F = \phi_F q/kT$ by the normalized effective quasi-equilibrium Fermi potential V_F^* We thus obtain

$$n^* = n_i^* \exp(-V_F^*) \tag{9}$$

$$p^* = n_i^* \exp(V_F^*) \tag{10}$$

where

$$V_F^* = \frac{V_P + V_N}{2} \tag{11}$$

is the so-called quasi-equilibrium effective Fermi potential

The main purpose of the present description is to analyse optical radiation effects on the MOSFET threshold voltage In order to achieve this purpose, we first have to combine quasi-equilibrium parameters n_i^* and V_F^* with the light excitation factor R, which is usually defined as [3]

$$R = \frac{\Delta n}{n_i} = \frac{\Delta p}{n_i} \tag{12}$$

Substituting eqn (12) into eqns (5) and (6), and realizing that $n = n_i \exp(-V_F)$, $p = n_i \exp(V_F)$, $n^* = n_i \exp(-V_N)$, $p^* = n_i \exp(V_P)$, as indicated in equations (2) and (7) respectively, the electron and hole quasi-Fermi levels are therefore given by

$$V_N = -\ln[R + \exp(-V_F)] \tag{13}$$

$$V_P = \ln[R + \exp(V_F)] \tag{14}$$

Substitution of these expressions into eqn (11) results in an effective quasi-equilibrium Fermi potential having the following form

$$V_F^* = \frac{1}{2} \ln\left[\frac{R + \exp(V_F)}{R + \exp(-V_F)}\right] \tag{15}$$

Substitution of eqns (13) and (14) into eqn (7) results in an effective intrinsic quasi-equilibrium concentration of the following form

$$n_i^* = n_i\{[R + \exp(V_F)][R + \exp(-V_F)]\}^{1/2} \tag{16}$$

It follows from relations (15) and (16) that as the generation level grows, the effective Fermi level approaches the middle of the energy gap and the effective intrinsic concentration increases

The effective quasi-equilibrium Fermi potential is plotted in Fig 2 as a function of the light excitation factor

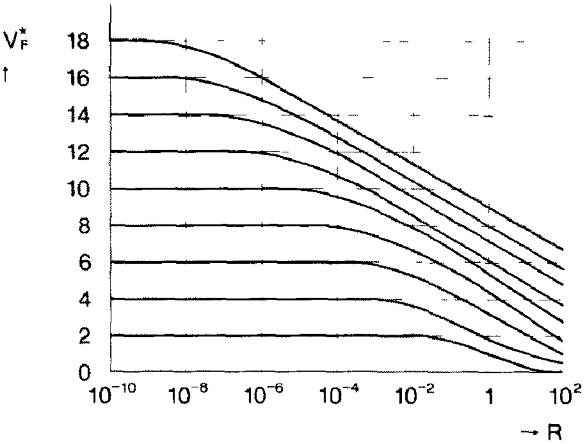

Fig 2 Normalized effective Fermi potential, V_F^*, *vs* light excitation factor R, with the normalized Fermi potential V_F in a non illuminated semiconductor as a parameter Note that $V_F = 18$ for the upper curve etc , for $V_F^* = V_F$ if R becomes zero

Again considering eqn (1), we see that the threshold voltage V_t depends on the light excitation factor through the Fermi potential

The equation for the effective threshold voltage V_t^* is

$$V_t^* = V_f + \frac{2kT}{q} V_F^* + \frac{2(\epsilon NkT|V_F^*|)^{1/2}}{C_{ox}} \tag{17}$$

Substitution of eqn (15) into eqn (17) results in an expression for the effective threshold voltage V_t^* as a function of R,

$$V_t^* = V_f + A_1\{\ln[R + \exp(V_F)] - \ln[R + \exp(-V_F)]\} + A_2\{\ln[R + \exp(V_F)] - \ln[R + \exp(-V_F)]\}^{1/2} \tag{18}$$

where

$$A_1 = kT/q, \quad A_2 = (2\epsilon NkT)^{1/2}/C_{ox} \tag{19}$$

Figure 3 shows the theoretical effective threshold voltage V_t^* as a function of the light-excitation factor for one of the investigated devices

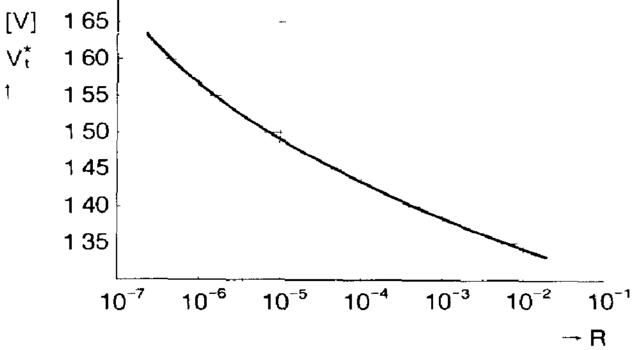

Fig 3 Calculated effective threshold voltage V_t^* as a function of light excitation factor R $T = 300$ K

3 Experimental

In order to verify the theoretical considerations given in Section 2 with practical experiments using MOSFETs under illumination, we need a relation that links the light excitation factor R with such experimental variables as optical radiation intensity, light wavelength etc

The light excitation factor R is not directly measurable, but could be accurately determined from the light-frequency C–V data [3] Based on Frankl and Ulmer's theory [4, 6], Pierret and Sah [3] have found the following for MOS Si–SiO$_2$ structures

$$R \simeq \left[\frac{\tau_{no}}{n_i h\nu}\,\frac{\alpha}{1+\alpha L_n}\right] I_{OR} = k_1 I_{OR} \tag{20}$$

where

τ_{no} = semiconductor minority carrier lifetime,

α = semiconductor absorption coefficient,

L$_n$ = minority carrier diffusion length ($L_n = (D_n\tau_{no})^{1/2}$ where D_n is the diffusion coefficient),

ν = frequency of the incident light,

I_{OR} = intensity of the optical radiation at the point of entry into the semiconductor

However, Pierret and Sah [3] also found that the light excitation factor R is not exactly proportional to I_{OR} but that it is almost proportional to $I_{OR}{}^{1\ 5}$, which means a significant deviation from the expected linear dependence

In our experiments we have used n-channel normally-off MOSFETs We used a standard LOCMOS technology with ion implantation facilities and (100) oriented wafers Other process parameters are stopper implantation $N_A = 5 \times 10^{16}$ cm^{-3}, gate-oxide thickness $d_{ox} = 75$ nm, polysilicon gate thickness $d = 0\ 5$ μm, threshold voltage ≈ +1 7 V

As light sources we used a helium–neon laser ($\lambda = 0.63$ μm) and a so-called ‘cold-light source’ type KL 150B from Schott-Main (F.R.G.). The light-meter was a fibre optics multimeter, model 22 LA produced by Photodyne Inc. (U.S.A.). Figure 4 shows experimental values of the threshold voltage V_t^* as a function of optical radiation intensity I_{OR} for the investigated MOSFET, of which the theoretical effective threshold voltage relation as a function of light excitation factor R is shown in Fig. 3. It can be concluded that the shapes of both the theoretical and experimental curves are in good agreement with each other.

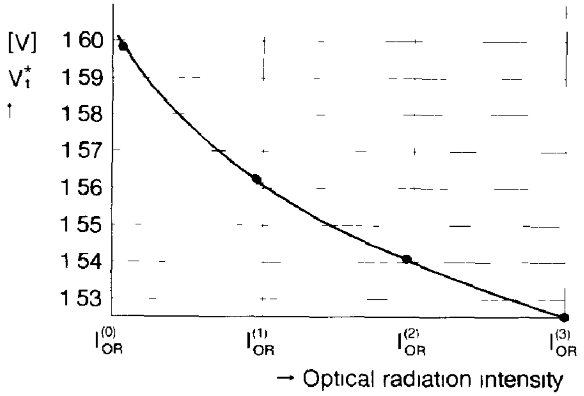

Fig. 4. Experimental values of threshold voltage V_t^* as a function of light intensity I_{OR} (linear scale). Intensity $I_{OR}^{(3)}$ corresponds to approximately 0.4 μW/mm^2. $T = 300$ K, $V_d = 0.5$ V.

4. Conclusions and discussion

Using monochromatic illumination, the threshold voltage photoresponse of n-channel MOSFETs has been investigated and compared to the theoretical predictions.

In general, the theory has been found to describe qualitatively the observed threshold voltage modulation of the MOSFET device due to illumination. Agreement between theory and experiment, however, is only qualitative. Quantitative agreement between theory and experiment is impaired by the fact that the constant k_1, as introduced in eqn. (20), is not known.

Additionally, it should be noted that this constant k_1 depends strongly on the properties of the silicon, which impairs the possibility of comparing our results with those of Pierret and Sah [3], for example.

We believe that by using MOSFET structures under monochromatic illumination, we can carefully estimate the light excitation factor R by measuring the threshold voltage shift.

In our experiments we also used ISFETs with a sandwich dielectric of SiO_2 and Al_2O_3 or SiO_2 and Ta_2O_5. Their behaviour under illuminated conditions was similar to that of the MOSFET Therefore we conclude that the theoretical procedure proposed here may be useful in the analysis of the threshold voltage of all MOSFET-based sensors under illumination

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Biographies

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The subject of his dissertation was the ion-sensitive field-effect transistor (ISFET) and the OSFET He is involved in research on electronic measuring and stimulating methods in physiological systems, with special attention on *in vivo* biosensors He lectures on biomedical instrumentation to graduate students of Twente University of Technology and medical personnel of affiliated hospitals

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