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Calculating double-exponential diode model parameters from previously extracted single-exponential model parameters

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Indexing terms: Diodes, Semiconductor device models

A procedure is proposed to calculate both pre-exponential reverse currents of the double-exponential model of a diode's current-voltage experimental characteristics from previously extracted reverse current and diode quality factor of the diode's single-exponential model. The procedure is illustrated by modelling the drain-body junction of a MOSFET including its parasitic series resistance.

Introduction: The simplest way to model a real diode containing a parasitic resistance in series with its junction is by using a modified single-exponential Shockley expression of the form

$$I = I_0\left[\exp\left(\frac{V - IR}{nV_t}\right) - 1\right] \tag{1}$$

where I is the current, V is the applied or extrinsic voltage, I_0 is the reverse current, R is the parasitic resistance, n is the so-called junction quality or ideality factor, and V_t is the thermal voltage, kT/q. However, frequently the experimentally measured I-V characteristics of a real diode exhibit an obvious double-exponential behaviour. In that case, if a single-exponential model is still imposed on its I-V characteristics, the resulting I_0 and n will not be unique because they will depend on the region or point in the characteristics chosen to perform the fitting or extraction algorithm. Theoretically the factor n will change from values near 2 at low forward voltages to values near 1 at higher voltages. Concurrently, the pre-exponential term I_0 will also change from high to low values. These limit-values of I_0 in the single-exponential model correspond to the I_{02} and I_{01} pre-exponential parameters of the diode's double-exponential model:

$$I = I_{01}\left[\exp\left(\frac{V - IR}{V_t}\right) - 1\right] + I_{02}\left[\exp\left(\frac{V - IR}{2V_t}\right) - 1\right] \tag{2}$$

By representing the total diode current as the superposition of two currents, as in the above equation, it is possible to separately model the contributions of two different conduction mechanisms that may be significant in the diode in question.

The pre-exponential I_{01} and I_{02} parameters of the double-exponential model of eqn. 2 could conceivably be extracted in the conventional way by extrapolating $\ln(I)$ against V to $V = 0$ at regions where the slope of the plot, $1/n$, reaches 1 and 0.5, respectively. However, these regions are often absent from experimental data, because the approximation $I >> I_0$ imposed by this and most extraction methods is not valid at lower voltages, and high injection effects, neglected by the model, dominate the experimental characteristics at higher voltages. Therefore, it would be useful to be able to extract I_{01} and I_{02} of the double-exponential model from within the region of the I-V characteristics where the approximation $I >> I_0$ is already valid and high injection effects are still negligible, a region where n has a value between 2 and 1; the procedure presented below enables us to do so by using values of I_0 and n of the single-exponential model previously extracted at a certain point of the experimental I-V characteristics within this region. There are several well known techniques [1] for extracting I_0 and n, generally from derivatives of the I-V data. When the parasitic series resistance is high it is convenient to use any of the various available methods [2–6] that are not affected by its presence.

Proposed procedure: In the range $I >> I_0$ the −1 term in eqn. 1 can be neglected, so that the diode quality factor n can be expressed as

$$\frac{1}{n} = V_t\frac{\partial(\ln I)}{\partial V_i} \tag{3}$$

where $V_i = V - IR$ is the intrinsic voltage across the junction. The derivative of the logarithm of eqn. 2 with respect to V_i can now be substituted into the right-hand side of eqn. 3 and, after some manipulation, the two pre-exponential terms of eqn. 2 can be solved as

$$I_{01} = \frac{2-n}{n}I^{(1-n)}I_0^n \tag{4}$$

$$I_{01} = \frac{2n-2}{n}I^{(1-n/2)}I_0^{n/2} \tag{5}$$

Although n and I_0 are both functions of I, the resulting I_{01} and I_{02} are assumed to be constant within the region of validity of the model. Therefore, it will suffice to extract n and I_0 at any one point of the data inside this region and proceed to evaluate eqns. 4 and 5 to obtain the double-exponential model parameters. Should there be any doubts about the location and width of this region of validity, the equations could be evaluated at several forward currents, taking as meaningful only those results that remain reasonably constant. If needed, a simple error minimising algorithm could be easily devised for deciding the best choice of I_{01} and I_{02} pairs.

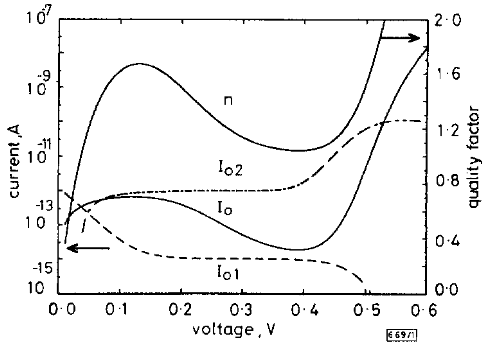

Fig. 1 *Extracted single-exponential and double-exponential model parameters of a diode simulated using eqn. 2 with $I_{01} = 10^{-14}$ A, $I_{02} = 10^{-12}$ A, $R = 10^4\,\Omega$ and $kT/q = 0.026$ V*

Single-exponential: n, I_o
Double-exponential: I_{o1}, I_{o2}

Validation of procedure: A hypothetical double-exponential diode was simulated using eqn. 2. Its single-exponential parameters n and I_0 were extracted from $\ln(I)$ against V and are shown in Fig. 1 together with its I_{01} and I_{02} double-exponential parameters, calculated using eqns. 4 and 5. The region of validity where I_{01} and I_{02} remain constant is clearly visible in the Figure. It corresponds to the voltage range where the quality factor plot decreases towards 1 from values near 2. It is also apparent from this Figure that n reaches neither 1 nor 2, and I_0 reaches neither I_{01} nor I_{02}, indicating that in this case it is impossible to obtain the double-exponential parameters directly by extrapolating the $\ln(I)$ against V plots.

To illustrate the use of the procedure on real diodes, the drain-body junction I-V characteristics of a Siliconix SD210DE MOSFET were measured. This junction represents an extreme test for the procedure because it exhibits double-exponential behaviour with close values of I_{01} and I_{02} and a very high series resistance. At a forward current $I = 2.45 \times 10^{-10}$ A, the extracted single-exponential model parameters are $n = 1.40$ and $I_0 = 1.77 \times 10^{-12}$A. From these values the pre-exponential terms of the double-exponential model were calculated, using eqns. 4 and 5, to be $I_{01} = 1.04 \times 10^{-13}$ A and $I_{02} = 4.44 \times 10^{-12}$A. The series resistance can also be obtained, once these values are known, for example, from the difference between the I-V characteristics of eqn. 2 calculated without series resistance and the measured I-V characteristics. Although the resulting parasitic series resistance of this diode exhibits considerable nonlinear behaviour at high current, for the purpose of this analysis it was assumed constant and equal to $1.7 \times 10^5 \Omega$. The good fit between the double-exponential modelled I-V characteristics and the experimentally measured data is shown in Fig. 2. The single-exponential model fit is also included for contrasting purposes.

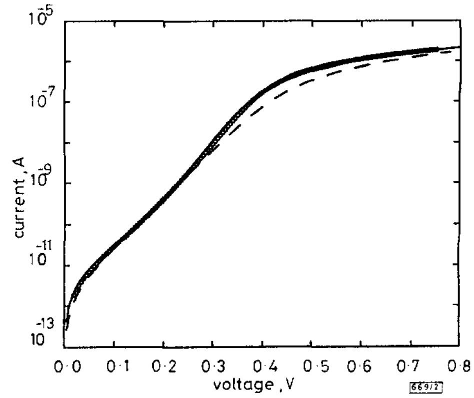

Fig. 2 *Measured and modelled I-V characteristics of MOSFET drain-body junction*

The models' parameters used are indicated in the text.
o measured
- - - - modelled, single-exponential
——— modelled, double-exponential

Conclusions: The simple formulas proposed enable us to quickly calculate the two reverse currents of a diode's double-exponential model if the values of the n and I_0 parameters of its single-exponential model are already known or can be extracted at some convenient point in the measured diode's forward I-V characteristics.

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Carrier trapping in inter-polysilicon charge injectors

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Indexing terms: Polysilicon, Electron field emission, Silicon dioxide

The authors report the observation of trapping and aging effects in charge injection schemes for floating-gate devices. The observations indicate that these polysilicon charge injectors must be used in conjunction with a programming technique which includes feedback. A suitable scheme is chip-in-the-loop training.

Floating-gate devices fabricated using a standard double polysilicon process have been proposed as suitable for trimming analogue circuits [1], and for analogue information processing architectures, such as the radial basis function network [2]. Our particular interest is in developing a nonvolatile form of a Euclidean distance calculating circuit which has been demonstrated using a pass transistor to establish charge on the 'floating-gate' [3]. The advantage of this volatile implementation is experimental simplicity, however nonvolatile devices offer considerable system benefits, including long data storage times [4], and increased maximum throughput.

One possible charge injection ('programming') technique is based on charge flow across the thick oxide between two layers of polysilicon [5]. Within the Euclidean distance cell the floating-gate potential must be set to a particular value, typically 0.85V, in order for the circuit to operate correctly. A programming scheme which could achieve this is based on two injectors each with a programming voltage of opposing polarity (Fig. 1). Ideally, these injectors will achieve dynamic equilibrium only when the floating gate is at the desired voltage.

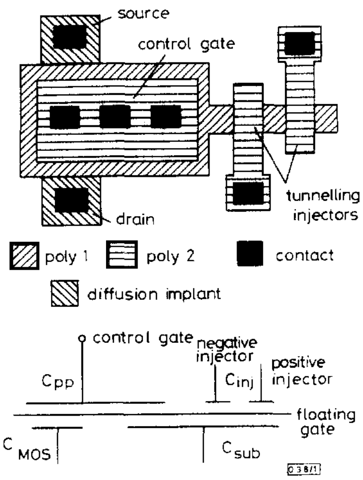

Fig. 1 *Layout and schematic diagram of standard-process floating-gate MOSFET with two tunnelling injectors*

To optimise the design of the injector structures, experiments were performed on injectors fabricated using a MOSIS-compatible 2μm double polysilicon process. Unlike previous experiments which relied on programming with voltage pulses, our results were obtained by employing a fixed programming voltage. The programming voltage, typically of the order of ±12V, was applied to a single injector. This resulted in charge injection onto the floating gate which causes a change in the floating-gate potential, reducing the field across the injector. The current-voltage characteristics of the charge injection mechanism can then be determined from the time dependence of the floating-gate potential. Unfortunately, owing to its electrical isolation, a direct measurement of the floating-gate potential is impossible. Our approach was therefore based on monitoring the time dependence of the drain current during programming. Once programming was completed a feedback loop