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Transient Two-Dimensional Numerical Analysis of the Charge-Pumping Experiment

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Abstract

A transient model of the charge-pumping experiment on bulk MOSFET's and SOI devices has been developed. It is based on the self-consistent numerical solution of the time-dependent basic semiconductor equations including the trap dynamics equations, assuming arbitrary voltage pulses at the terminals. In this paper some details of the approach are presented. The model is applied to study the non-ideal (geometric) components in the charge-pumping current for the two-dimensional cases. Additional applications of the presented charge-pumping simulation are pointed out.

1. INTRODUCTION

The charge-pumping method [1] is used to analyze interface states created by non-uniform hot-carrier injection, by irradiation or Fowler-Nordheim injection in MOSFET's and memory devices ([2]), as well as to monitor the interface traps at both the front and the back interface in different SOI devices [3,4]. Charge pumping can be applied to study bulk traps in SOI films and traps at the grain boundaries in the polysilicon films [5] as well. Different charge-pumping techniques have been developed: the large-signal methods based on the non-steady-state emission process ([6]) and on the surface potential ([7]); the small-signal rectangular pulse technique [8], and the pulsed interface probing techniques [9]. These procedures rely on analytical expressions, which are approximate, but which enable an efficient processing of the experimental data.

The approach presented in this paper enables one to calculate the terminal charge-pumping currents for the assumed trap distributions, physical model of traps, device geometry, doping profile and terminal voltage pulses. To the best of our knowledge, it accounts for the first time for the several effects in the charge-pumping experiment pointed out in the literature: the finite time for the minority carrier response to the terminal bias variations, which produces the geometric [1,6,7] and dimensional [3] current components in conventional MOSFET's and SOI devices in the large-signal techniques and a non-uniformity along the interface in the small-signal methods [8]; the 2D effects due to nonuniform spatial trap distributions and eventual lateral current flow [10]; variable charge-pumping threshold U_{th}^{cp} and charge-pumping flat-band voltage V_{fb}^{cp} and, therefore, variable emission times in the junctions [6]; energy-dependent capture cross sections; and additional deviations from the simple theory [7,9,11].

2. MODEL

Our approach is based on: (1) The numerical solution of the time-dependent basic semiconductor equations. The continuity equations are discretized in time by the backward-differencing method. At the beginning of a new time-step the decoupling algorithm proposed in [12] is applied using the total current continuity equation instead of the Poisson equation. After the chosen accuracy has been achieved the time-dependent Gummel-algorithm is used to obtain the final solution. Thus, the Poisson equation is solved with an accuracy which is independent of the actual time-step. This approach originates from the idea proposed in [13]. It has shown an absolute stability and a high efficiency in all transient simulations we carried out for different MOS devices and a variety of the terminal pulses. (2) An accurate terminal current calculation in the transient cases is used, which is based on the local concentration-dependent weighting functions. These functions are required to have a minimal gradient in the device areas with a high carrier concentrations, since the current densities are inaccurate in these parts of device. We obtain the weighting functions by minimization of certain quadratic functionals which depend on the carrier concentrations. (3) Trap dynamics are described by the Shockley-Read-Hall equations. They are solved in time by a backward-differencing discretization. The corresponding generation-recombination rates for electrons and holes are coupled with the transient continuity equations, while the dynamic trapped charge is coupled with the Poisson equation. The system is solved self-consistently. A method is developed to achieve a stable and efficient convergence even at very high trap densities (e.g. for interface traps with density $D_{it} \sim 10^{13}/cm^2eV$). It consists of using the derivation of the trapped-charge in transient conditions with respect to the potential and the derivation of the generation-recombination rates with respect to the carrier concentrations to improve the convergence of the discretized Poisson equation and the continuity equations, respectively. Arbitrary interface and volume trap distributions can be discretized in energy and position space. We simulate the experimental procedure directly, applying transient pulses at the terminals. After the simulation lasting a few signal periods, the time averages of the interface effective generation of electrons and holes $\overline{G_{\text{eff}n}}, \overline{G_{\text{eff}p}}$, and of the terminal currents $\overline{i_b}$, $\overline{i_d}$, $\overline{i_s}$ and $\overline{i_g}$ are calculated. The time averaging is performed in the period for which the periodic steady-state condition holds: $\overline{G_{\text{eff}n}} = \overline{G_{\text{eff}p}}$, $I_{cp} = \overline{i_b} = \overline{i_d} - \overline{i_s}$, $\overline{i_g} \ll I_{cp}$, where I_{cp} is the charge-pumping current. Note that we simulate an aperiodic and not a periodic signal. By analyzing the electron and hole components in the terminal currents and the generation rates, a deviation from the 'ideal charge pumping theory' can be extracted in each particular case.

3. GEOMETRIC COMPONENTS

Based on an intensive study, we have explained the geometric components in I_{cp} for the 2D cases ($L_{eff} \ll W$) in the large-signal charge-pumping techniques. Notice that the measured charge-pumping current is a sum of the DC components of the bulk hole and electron currents $I_{cp} = \overline{i_{bh}} + \overline{i_{be}}$. For n-channel bulk MOSFET's the following conclusions can be drawn (Figs.1-6):

$\overline{i_{bh}} = \overline{G_{\text{eff}n}} = \overline{G_{\text{eff}p}}$. There is no additional increase of $\overline{i_{bh}}$ due to the short fall time t_f. An increase of $\overline{i_{bh}}$ and $\overline{G_{\text{eff}(n,p)}}$ due to an extended electron-hole recombination over the interface traps at the beginning of the hole capturing, which can occur at short t_f (when a large amount of the inversion-layer electrons still remain close to the interface), is negligible. This effect is demonstrated for an extreme case in Fig.2. High electron and hole concentrations coincide at the interface in time much shorter than the corresponding electron and hole capture time constants. Contrary to the claim in [7,11], the geometric component due to short t_f cannot be explained by this effect. The geometric component originates exclusively due to $\overline{i_{be}}$. It is manifested as an increase of $\overline{i_{de}} + \overline{i_{se}}$ as well. The component $\overline{i_{dh}}$ is negligible. Transfer of electrons from the interface towards the bulk contact during t_f is produced by a gradient of the quasi-fermi level normal to the interface F_n. These electrons can originate from two sources.

The first are inversion-layer electrons which remain in the channel due to the short t_f – as already discussed in [1,7] and numerically simulated in [14]. F_n is produced by the very fast response of the majority carriers – depletion region overshoot [7]. Electrons are transferred by the (dominant) diffusion in a very short time. This component is strongly dependent on the top gate voltage (actually $\Delta U_G/t_f$). The second effect is the transfer of electrons emitted in the channel from the interface traps during the non-steady-state emission, Fig.3 and 4. An assumption, established in the literature, is that the emitted electrons just travel to the source/drain junctions [6,7,9,10]. However, some part of

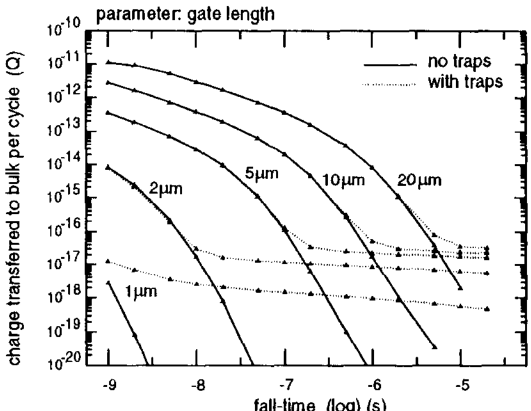

Figure 1

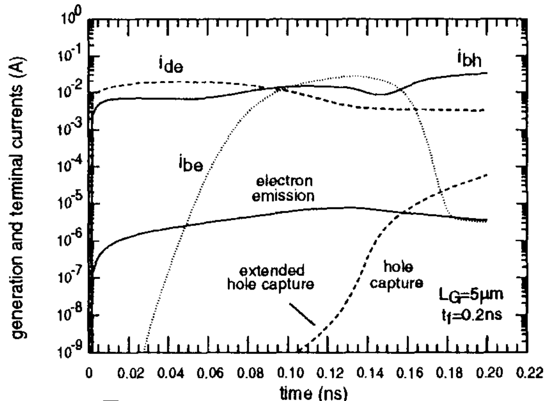

Figure 2

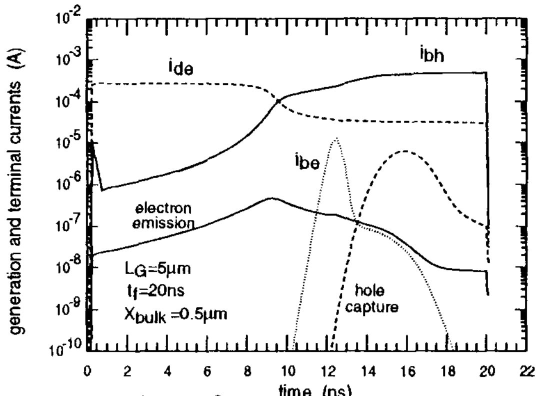

Figure 3

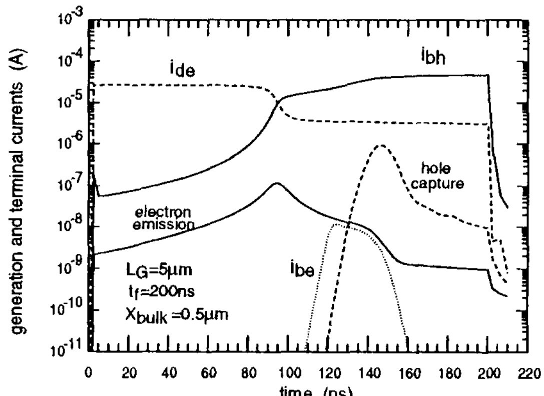

Figure 4

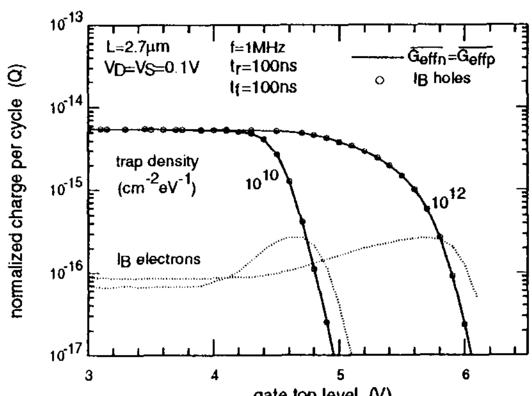

Figure 5

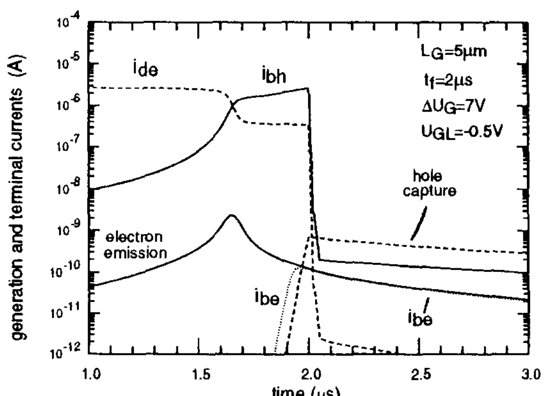

Figure 6

these electrons will travel to the bulk, thus contributing to I_{cp}. This effect is proportional to the interface-trap density and independent of the top gate voltage. At short t_f, this transfer is due to the depletion region overshoot, as for the channel-electrons. At long t_f (Fig.4) and/or during the low gate-pulse level (Fig.6), the responsible driving force F_n is produced by the hole current towards the interface due to hole capturing at the interface. Consequently, in the presence of the interface traps, $\overline{i_{be}}$ does not vanish at long t_f, Fig.1 and 4. When switching between strong inversion and strong accumulation this effect represents only a small correction to I_{cp}, Fig.5. However, when weak hole capturing occurs, as at the falling edge of the $I_{cp}(U_{GL})$ curve (Fig.5), the component $\overline{i_{be}}$ can significantly contribute to I_{cp}. In the example given in Fig.6: $\overline{i_{be}} \approx 0.1 \cdot \overline{i_{bh}}$, while for $U_{GL} = -0.2V$ it follows $\overline{i_{be}} \approx 4.6 \cdot \overline{i_{bh}}$. The generation of $\overline{i_{be}}$ during the fall-time and the low gate-pulse level could have an influence in the three level techniques [7,11] and in the pulsed-interface-probing techniques [9], when the middle/low gate-pulse level is sufficiently low. Note that no 'non-ideal behavior' has been found during the rising edge of the gate-pulse, even for very short t_r.

4. CONCLUSION

A numerical model of the charge-pumping experiment has been developed and applied to investigate the parasitic (geometric) components in the terminal currents in bulk MOSFET's for the large-signal techniques. In addition, we have applied it to study several problems like e.g. the changes of the charge-pumping curves after the localized damaged region is created; to examine the accuracy of analytical models for I_{cp} and for the D_{it}(E)-extraction ([6]); to improve the expressions for the extraction of the spatial trap distribution from the charge-pumping experimental data; to analyse the charge-pumping curve of virgin and stressed LDD MOS devices, where our approach becomes indispensible to calculate the contribution from the LDD regions due to the gate-edge fringing effect; and to investigate the interface coupling and dimensional charge-pumping current components in thin-film SOI devices [15].

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