SOI Related Simulation Challenges with Moment Based BTE Solvers

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Abstract *- We discuss challenges particular to SOI simulation. We also show evidence of what we believe is hot carrier diffusion out of the channel near the drain, giving rise to a negative differential conductivity (NDC), or transient region in an I_D-V_D curve on SOI.*

Introduction

Silicon-on-insulator (SOI), a niche in the silicon semiconductor community until only a few years ago, appears to be moving rapidly toward the mainstream. Due to its lower junction capacitance, it offers a performance boost for a migrated bulk technology, along with benefits provided by electrical isolation. TCAD engineers are being asked to provide support in the design of devices in this material, as well as understanding of their operation. We will describe phenomena (some old, some new) which appear in SOI devices that challenge the transport models beyond what bulk device simulation has heretofore done.

Transport Models

It can reasonably be asked whether accurate transport models exist for everyday use by TCAD engineers,[1] given the rather bleak assessment by several groups (see for instance [1-3]). Some of the early critical analyses focused on the infamous one-dimensional n^+-n-n^+ diode [1,4], a rather poor device for comparing transport models to be used for MOSFETs. Not only are the carrier densities orders of magnitude below those found in today's FET channels, but also the neglect of surface roughness scattering render this structure questionable for this puspose. Nonetheless, these analyses have demonstrated some rather serious problems for the moment-based models, and some have suggested ways to improve the hydrodynamic[2] (HD) transport model [4,5]. Although more recent MC analyses on a MOSFET [2] appear to suggest a more Maxwellian distribution than the equivalent analysis on the n^+-n-n^+ diode [1], nevertheless the situation appears somber.

Drift-diffusion (DD) appears to still be the model of choice by most TCAD engineers (for bulk simulation), given that it somehow manages to predict terminal currents better [3] than models which include higher moments of the Boltzmann Transport Equation (BTE), in spite of its unphysical neglect of higher order phenomena, such as velocity overshoot. This can be addressed by scaling the saturated velocity with gate length, thereby negating any necessity of progressing toward more physically correct models as gate lengths continue to shrink. And although hydro provides more accurate prediction of impact- ionization, this is not a quantity which the typical, bulk device designer is overly concerned about.

Simulation of SOI devices presents greater challenges, primarily because even the slightest build up of charge can influence the body potential, and have profound effects on terminal currents. This is a situation which is vastly different than bulk. The substrate contact in bulk simulations removes excess charge, pushing the internal environment of the body back toward thermal equilibrium. The well known floating-body effect (accumulation of majority carriers in the body due to impact ionization) is one of these phenomena. Note that a typical SOI device will begin to show this effect between 0.7-0.8 volts on the drain, well below the band-gap of silicon, which appears to be explained by the high-energy tails of the distribution function [6]. This is one phenomenon which begins to point out that the situation is more critical in SOI simulation. The high energy tails of the distribution function are now beginning to affect the drain current in a significant way. This paper presents a new effect for SOI MOSFETs, which we believe is due to hot carriers, and will only be captured by a higher model such as HD.

Results

The diffusion coefficient in hydro simulations is much larger than in DD because of its dependence on carrier temperature. Carriers could diffuse into the body from the heated carriers near the drain, even in bulk. But now that they can accumulate in SOI, and change the body potential, it can have some unexpected results. The diffusion coefficient was relatively benign in bulk MOS simulation. Fig. 1 demonstrates this phenomenon in an SOI device (impact-ionization is turned off for both simulations to bring out the effects of the diffusion coefficient without the complications of impact-ionization). Since this is a long NMOS device (1 μm), one wouldn't expect differences between the two models, and they don't differ at the two extremes. When impact-ionization is turned off in the Stratton formulation [7], the only direct coupling between the continuity equation and energy equation is through the diffusion coefficient. This effect is qualitatively similar if one uses the Blotekjaer formulation [7] (not shown). The diffusing channel carriers recombine with majority carriers in the body, which is what gives this phenomenon a relatively long time constant (approximately on the order of milliseconds). This results in a change in body potential and a larger depletion region, as demonstrated in Fig. 2. This change in body poten-

1. We do not consider Monte Carlo solution of the BTE as an everyday tool for device design and analysis, although it can provide the most accurate transport models.
2. We lump all of the higher order (higher than drift-diffusion) moment methods into one, and collectively refer to them as the hydrodynamic (HD) model.

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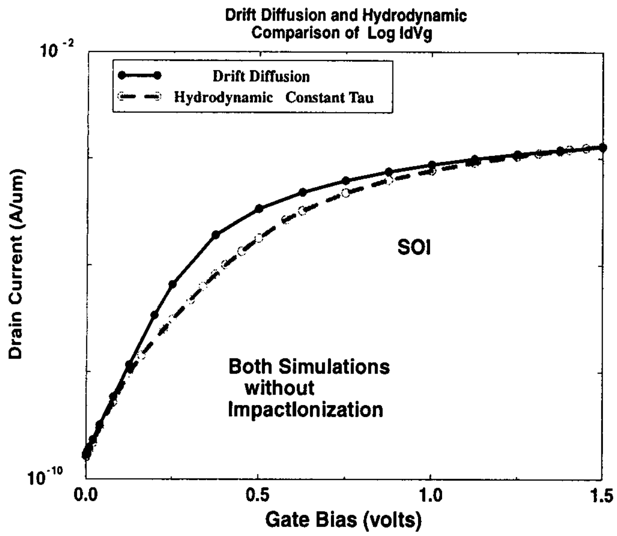

Fig. 1: 1 µm device. Drift-Diffusion (DD) and HydroDynamic (HD) (both without impact-ionization) log I_D-V_G comparison. Constant energy relaxation time of 0.3 ps. V_{DS} = 1.5 volts. The HD simulation shows a change in body potential from hot-carrier diffusion out of the channel, resulting in a decrease in drain current.

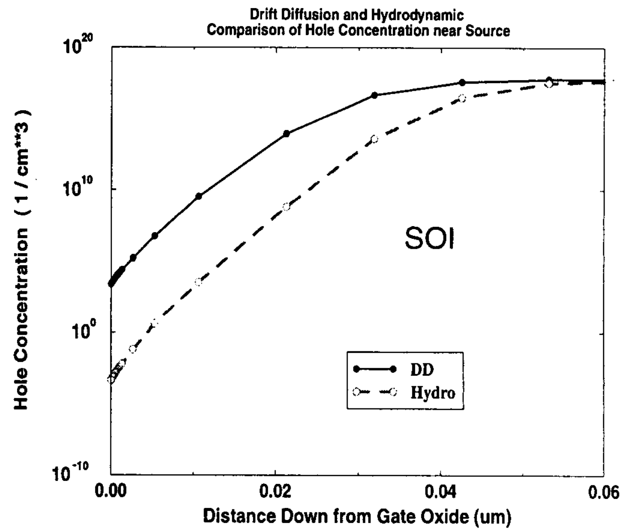

Fig. 2: Hole concentration near source for V_{GS} = 0.375 from Fig. 1. Note the differing depletion regions.

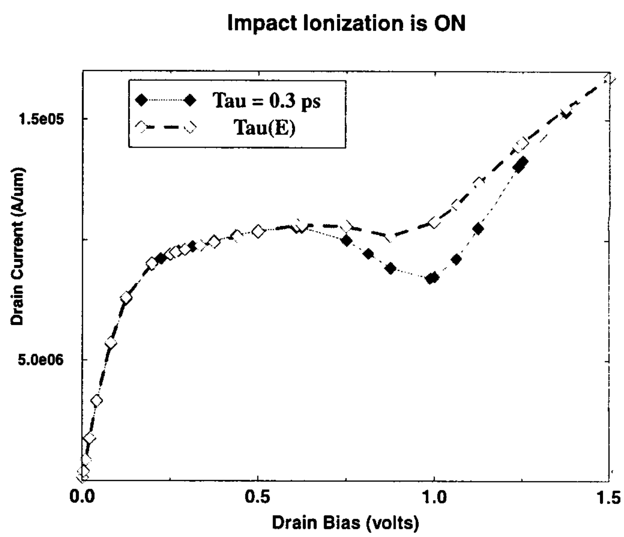

Fig. 3: HD (WITH impact-ionization) I_D-V_D sweep with a constant, and an energy-dependent relaxation time. The latter results in lower carrier temperatures and less diffusion of the hot carriers into the body.

tial can result in a negative-differential conductivity (NDC) region in I_D-V_D simulations, as shown in Fig. 3, where we have now included impact-ionization.

These results were very disconcerting when first discovered, and were originally attributed to a problem with the simulator, or the hydrodynamic model, until we found experimental evidence which suggested that the predicted NDC is present in SOI devices under the conditions close to those predicted by the HD model. Fig. 4 is experimental data taken on a long PMOS device which exhibits this behavior. Since this phenomenon is related to the recombination rate, it exhibits rather slow response times, which allow it to be studied with the HP4156 parametric analyzer. Curve "LONG" on Fig. 4 is performed in the long integration time mode of the 4156, which was on the order of 3 seconds per bias point (with the added delay time). "MEDIUM" is the medium integration time mode, and "SHORT" is short integration, which was on the order of 600 microseconds per bias point (no delay time). The gate bias was applied for three seconds before the drain was swept, to further rule out any possibility of generation currents. Note that the currents are extremely low, hence, it cannot be attributed to self-heating. Other possible explanations, such as generation in depletion regions would increase the drain current, not decrease it. Generation would have the same effect as impact-ionization; generated electrons migrate to the body (PMOS device), decreasing V_T, resulting in more drain current, not less. All attempts to explain this with anything other than hot-carrier diffusion have failed.

We were purposely measuring long devices to avoid complications of short-channel effects which dominate any NDC, so it was rather confusing when all transient effects disappeared on more recent lots. But HD simulations indicated that the transient was sensitive to the doping in the body, and that somewhere in the mid 10^{17} range, one lost all such effects (see Fig. 5). Recent lots had decreased well implant dose, while increasing halo dose, and explained the disappearance of any transient effects for the long devices. However, if this were truly a hot-carrier phenomenon, the short devices (where halos would push body doping back up) should still exhibit a transient effect, although NDC would be masked by short-channel effects. This hypothesis was borne out; the experimental data shown in Fig. 6 demonstrates that the transient effect is still present in short devices.

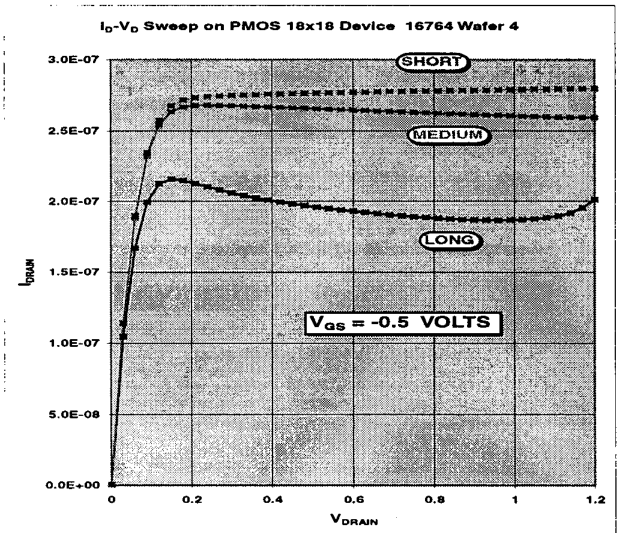

Fig. 4: Experimental data of a 10 μm PMOS device employing various integration times of the HP4156.

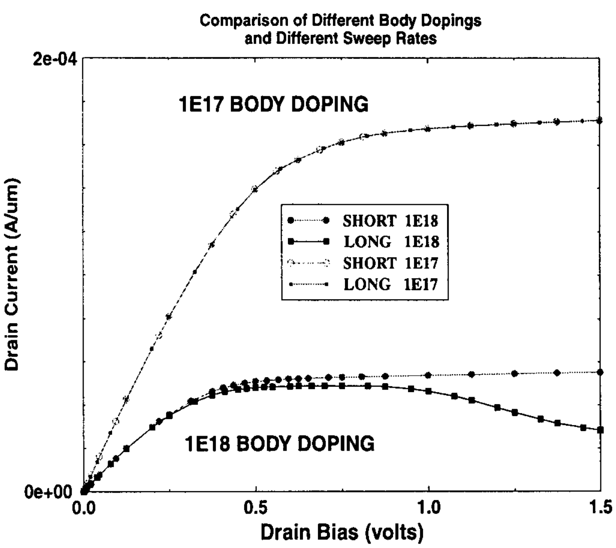

Fig. 5: Transient I_D-V_D sweep for constant body doping of 10^{17} and 10^{18}. LONG corresponds to 20 seconds from 0 to 1.5 volts, and SHORT corresponds to 1 millisecond from 0 to 1.5. Note the loss of any difference between the sweeps for the 10^{17} case.

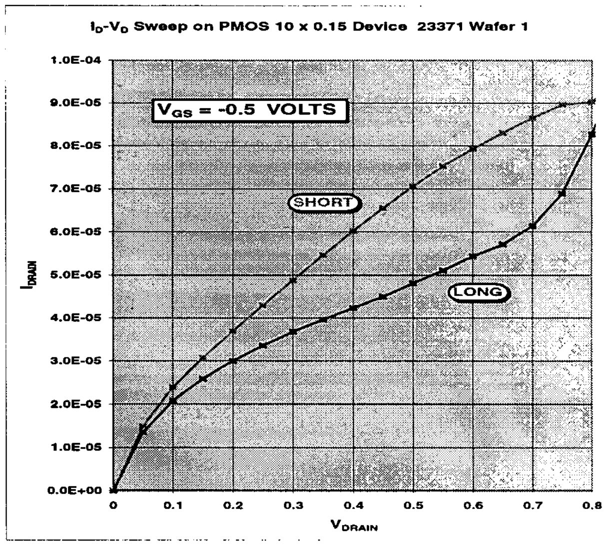

Fig. 6: PMOS device with gate length of approximately 0.15 μm from a later lot, which possessed lower well doping, but an increased halo dose, resulting in approximately the same body doping for the long PMOS device of Fig. 4.

Note that whereas the two devices of Fig. 5 have different V_T's, it should not be misconstrued that this phenomenon is limited to an extremely narrow (V_{GS} - V_T) range. V_{GS} of 0.5 (negative for PMOS) volts was chosen more for consistency throughout the paper, avoidance of the possibility of self-heating, and to stay above threshold, than that the effect disappears except for a region around threshold. We have experimental data (and simulation) well above and well below V_T displaying transient effects, but the analysis is more straightforward, for the above mentioned reasons, if one stays around a V_{GS} of 0.5 volts.

Monte Carlo simulators predict a non-constant energy relaxation time when the quantities of a relaxation time formulation are calculated [8]. A non-constant energy relaxation time capability has been added to Dessis [9], and this capability has been used in the I_D-V_D sweep shown in Fig. 3 labeled Tau(E) (we scale the relaxation times from [8] but keep the same basic shape). There is a decrease in the NDC, because the electron temperature is on average lower than for the constant case, which leads to a smaller diffusion coefficient, and less diffusion out of the channel near the drain.

One final note concerning the recombination time and its effects on the behavior of this phenomenon. Recombination can effect this transient behavior because it leads to a larger gradient in the carrier concentration and more diffusion. Fig. 7 demonstrates that different surface recombination velocities at the buried oxide interface have a large effect on the behavior of the I_D-V_D curve. And although not shown, changing the bulk recombination lifetime exhibits similar behavior. In fact, increasing bulk lifetime to unrealistically large values, results in the transient nearly disappearing. It is difficult to extend this

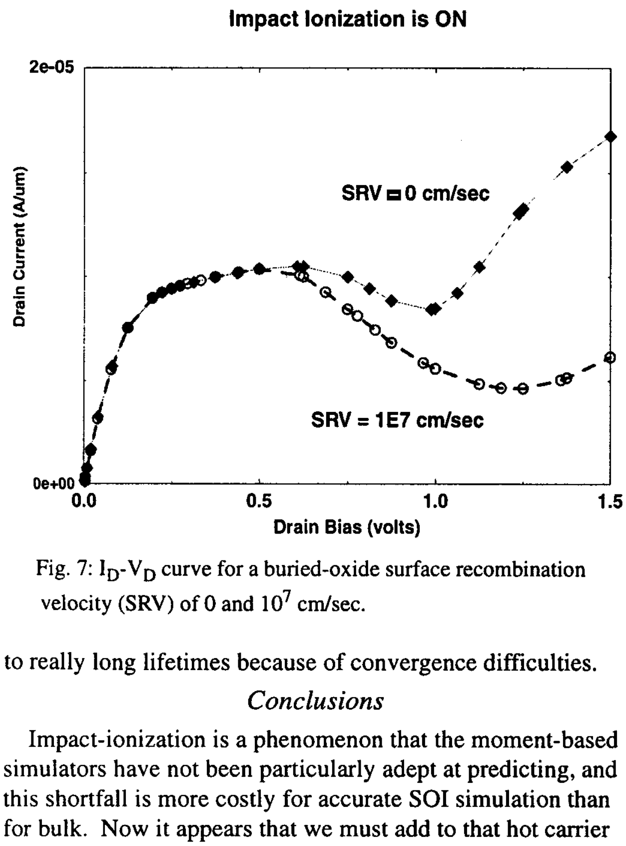

Fig. 7: I_D-V_D curve for a buried-oxide surface recombination velocity (SRV) of 0 and 10^7 cm/sec.

to really long lifetimes because of convergence difficulties.

Conclusions

Impact-ionization is a phenomenon that the moment-based simulators have not been particularly adept at predicting, and this shortfall is more costly for accurate SOI simulation than for bulk. Now it appears that we must add to that hot carrier diffusion, and the physical phenomena which tend to balance these. The interaction of impact-ionization, diffusion out of the channel (transient effect or NDC), Schockley-Read-Hall recombination, and surface recombination at the buried oxide interface, cannot be dealt with in isolation. They are all coupled. The transient, or NDC, effects in SOI devices provide an excellent vehicle for testing transport models, well beyond what bulk devices have provided. The transient effect is a two-dimensional issue; one-dimensional analyses, no matter how sophisticated, will not capture it. Although the HD model is seriously in error concerning the quantitative behavior of the transient effect (experimentally, it begins at lower voltages than predicted by HD), qualitatively it did predict that this phenomenon would be present, given the right conditions, in SOI devices, and also that it would disappear for lower body doping.

This phenomenon needs to be studied more thoroughly and verified via more accurate transport simulators. Unfortunately, Monte Carlo (MC) simulators will have a very difficult time to aid in this analysis, because of the very long times involved (on the order of milliseconds), and the fairly low amount of carrier diffusion it takes to begin to see effects. We believe that perhaps the best use of MC will be in tuning of the parameters in the HD models, and more sophisticated equations to capture high energy effects such as hot carrier diffusion.

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