A Physically Based Substrate Current Simulation

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Abstract

A Drift-Diffusion (DD) simulation is compared with a hydrodynamic (HD) simulation. The used device is a submicron n-channel MOSFET. The current density distribution in the area of maximal generation is calculated. The influence of a surface reduced impact generation rate model is discussed. Finally a generation rate which is proportional to the carrier concentration is calculated. This is in contrast to most used models were the generation rate is proportional to the particle flux density.

1. Introduction

The amount of substrate current is an important indicator for the aging behavior of the device. Small substrate currents can be attained by a careful design of the device doping. To calculate the substrate current it is necessary to use an accurate, physical motivated impact ionization model. The standard DD model uses a field-dependent impact ionization model. However, the electric field dependence is inaccurate especially in small devices. Nonlocal carrier heating must be taken into account when the typical thickness of space charge regions becomes comparable with the carrier energy relaxation lengths.

To calculate the local impact generation rate more appropriately the local carrier temperature has to be used instead of the electric field. The carrier temperature can be calculated using Monte Carlo simulations or HD simulations. With the carrier temperature an equivalent electric field is computed using results from Monte Carlo calculations for the electric field versus temperature characteristic. Finally, the equivalent electric field is used in combination with a conventional DD model to calculate the generation rate with the well known exponential law [4].

When simulating substrate currents often an impact ionization model is applied which accounts for a reduction of the surface generation rate [2][4]. The important influence of this surface reduction model can be seen when the substrate current is calculated for different gate voltages where the drain voltage is held constant. This investigation shows a decay of the substrate current for increasing gate voltages which can be attributed to a shift of the current density away from the region where the ionization coefficients have their maximum value.

2. The simulated device

The investigated devices are LDD-Pocket N-channel MOSFET test structures ($\mathrm{L_g} = 0.4\,\mu\mathrm{m}, 1.0\,\mu\mathrm{m}$) for which detailed substrate current measurements were performed. During the measurements the substrate and source contacts were grounded. The doping profiles were generated with two-dimensional process simulation and have been verified by comparison of the measured and simulated output characteristics. The maximum of the LDD doping is slightly below the semiconductor-spacer interface. At low gate voltages, the pinch-off point is located closer to the source side and the maximum current density is in the LDD-doping region rather than beneath the surface.

3. The substrate current analysis

The influence of a surface impact ionization model can be estimated, when we look at a vertical section of the current density in the maximum generation point. Fig. 1 and Fig. 2 show that there is a sharp local maximum of the current density in the DD model. In the HD model the current density is much smoother. At low gate biases (Fig. 1) the maximum current density is in the LDD-doping region rather than beneath the surface. At high gate biases (Fig. 2) the maximum current density moves towards the surface. When we compare the two figures, it can be seen that the shift of the relative current density is much higher in the DD model than in the HD model. The broadening of the current density in the HD model is caused by the high diffusion of the carriers after reaching the pinch-off point. This effect can be explained when the partial driving forces of the DD model (1) are compared with the partial driving forces of the HD model (2). The driving force for electrons with a concentration n reads in the DD model (analogous for holes):

$$\vec{F}_{DD} = -\mathrm{grad}\,\psi + \frac{k_B \cdot T_0}{q} \cdot \frac{1}{n}\mathrm{grad}\,n \tag{1}$$

Note that the prefactor to the concentration gradient depends on the lattice temperature T_0 which is usually set constant. In homogeneous materials the HD model uses a driving force which depends on the additional carrier temperature gradient.

$$\vec{F}_{HD} = -\mathrm{grad}\,\psi + \frac{k_B \cdot T_n}{q} \cdot \frac{1}{n}\mathrm{grad}\,n + \frac{k_B}{q} \cdot \mathrm{grad}\,T_n \tag{2}$$

The prefactor to the concentration gradient in the HD model now depends on the electron temperature T_n. Comparing the two prefactors of the concentration gradients, it can be seen that the factor in the HD model can be much larger especially in the high temperature range. The influence of the grad T_n term in the HD model is small compared with the grad n term. The reason for this is the small vertical gradient of the electron temperature in the region of interest.

Therefore, when the generation rate is calculated, the influence of the surface reduction in the HD model is much smaller compared to the conventional DD model.

A recent publication [1] also shows that the reduction of the surface generation rate is much smaller than published in earlier works. This agrees well with our HD simulations (Fig. 1, Fig. 2).

Because of the above mentioned reasons we have calculated the substrate current using a hydrodynamic bulk ionization model even in the channel region. The model is based on the work of [3]. The advantage of this model is that the calculated generation rate is proportional to the carrier concentration and not to the particle flux density. This is physically more motivated because the saturation velocity is much smaller compared to the thermal velocity. The model is implemented in a self-consistent manner, i.e., the energy flux equations account for carrier cooling.

The used equation for the electron generation rate depending on the concentration n reads:

$$G_n\left(n, T_n\right) = n\,A\,\exp(B\,u)\left[\left(1 + \frac{1}{2}u\right)\mathrm{erfc}\left(\frac{1}{\sqrt{u}}\right) - \frac{1}{2}\sqrt{u}\,\exp\left(\frac{-1}{u}\right)\right] \tag{3}$$

$$u = u\left(T_n\right) = \frac{k_B\,T_n}{E_{th}} \qquad B = \frac{C\,k_B\,T_0}{E_{th}} \tag{4}$$

The electron temperature strongly depends on the used energy relaxation time which is assumed to be $\tau_n = 0.4$ps. The parameters A and C have to be calibrated to give best agreement with the measurements. The best correspondence with the measurement is found when using the values for $\mathrm{A} = 4.53 \cdot 10^9\,\mathrm{s}^{-1}$ and $\mathrm{C} = 0.416$.

For the threshold energy E_{th} the value 1.12eV is used.

The simulation results are shown in Fig. 3 and Fig. 4. The electron temperature in the maximum generation point increases from 2690 K (0.4μm device $V_D = 2\mathrm{V}, \mathrm{V_G} = 3\mathrm{V}$) up to 7750 K (0.4$\mu$m device $V_D = 3.3\mathrm{V}, \mathrm{V_G} = 0.6\mathrm{V}$). The highest generation rate is about $2.33 \cdot 10^{28}\mathrm{s}^{-1}\mathrm{cm}^{-3}$ (0.4μm device $V_D = 3.3\mathrm{V}, \mathrm{V_G} = 1.4\mathrm{V}$) and the smallest generation rate in the maximum generation point is about $5.62 \cdot 10^{24}\mathrm{s}^{-1}\mathrm{cm}^{-3}$ (0.4μm device $V_D = 2.0\mathrm{V}, \mathrm{V_G} = 0.6\mathrm{V}$)

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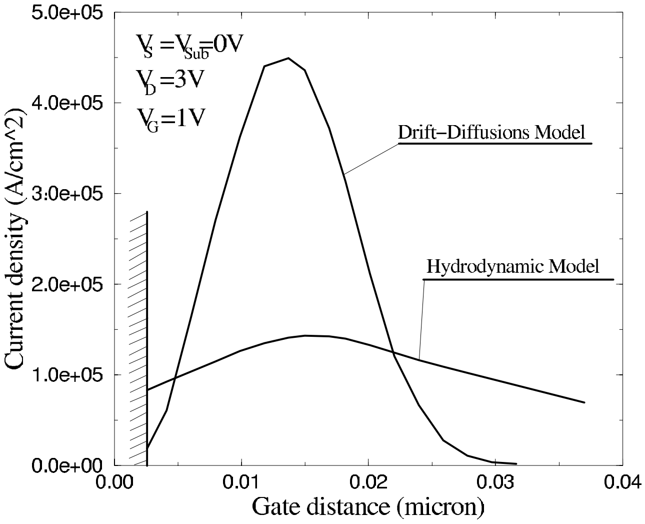

Figure 1: Current distribution in the maximum generation point at low gate bias

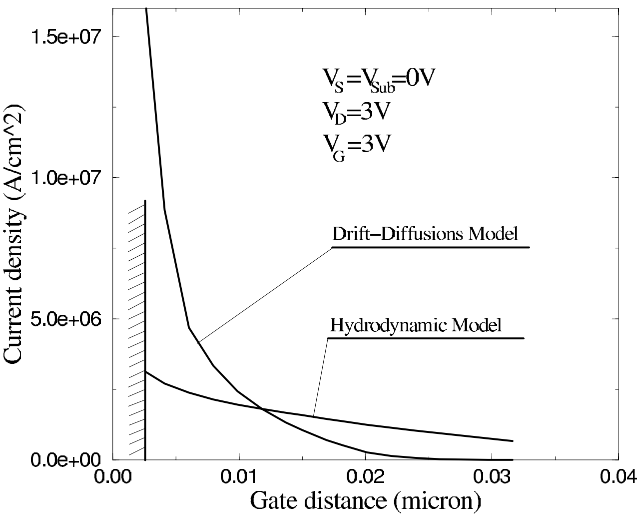

Figure 2: Current distribution in the maximum generation point at high gate bias

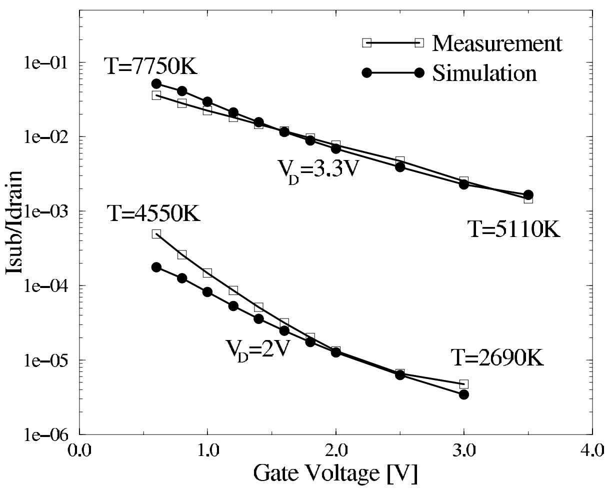

Figure 3: Multiplication factors for the 0.4 μm device ($V_S = V_{Sub} = 0$V). Electron temperatures are values in the points of maximum generation.

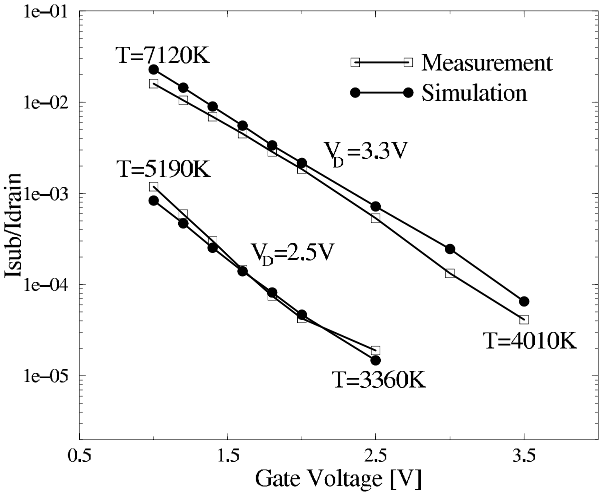

Figure 4: Multiplication factors for the 1.0μm device ($V_S = V_{Sub} = 0$V). Electron temperatures are values in the points of maximum generation.

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