P:31 A mobility model for TCAD simulation of current variation by random discrete dopant

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As the device size is rapidly scaling down , the variation of the drive current by random discrete dopant (RDD) becomes very important [1]. Contrary to the conventional MOSFET where the RDD in the channel region mainly contributes to the performance variations, the RDD fluctuation in the source/drain area can significantly influence the performance of the DRAM cell because the source/drain doping concentration needs to be kept low in the DRAM cell in order to suppress the junction and gate induced drain leakage (GIDL) [2].

The drift-diffusion (DD) solver can give unphysical results when it is applied to study the influence of the RDD without care because the adopted mobility models were typically derived from the homogeneous doping concentration, and they may not be valid when the atomistic doping profile is employed. Several groups are trying to solve these artifacts [3]. In this paper, we propose a method that can effectively eliminate these artifacts by correcting the doping dependent mobility model.

As a test structure, we consider a n-type silicon resistor of dimensions 20 nm × 20 nm ×140. Several random samples are generated with different dopant positions on intrinsic silicon for the given doping density. Discrete region length is 100nm. A continuous doping region is interposed between the contacts and the discrete zone to avoid any influence related to the boundary conditions. To resolve the carrier localization by discrete dopant, density gradient (DG) method with fine mesh is adopted [4]. As a reference, a continuous doped resistor with the same concentration as the discrete one was prepared. [Fig. 1-(a)]

For the low-field doping dependent mobility model, the Masetti model [5] is employed. As for the high-field saturation, we adopt the driving force from the gradient of the quasi-Fermi potential in order to avoid errors due to local electric field from individual dopants. The bandgap-narrowing (BGN) model is turned off. Fig. 2 compares the current of the resistor as a function of the doping concentration obtained from the reference continuous doping profile and from the ensemble average of the discrete dopant profiles.

When the doping-dependent mobility model is used together with the discrete doping profile without any correction, the model overestimates the current as there exist many mesh elements without any doping such that current can flow through the intrinsic path. In addition, this behavior is sensitive to the mesh spacing such that it is very difficult to obtain a robust and consistent result. In order to resolve this issue, we smooth the discrete doping profile for the mobility calculation by applying the Sano method [6] where the cut-off parameter (Kc) is calibrated as a function of the doping concentration in order to reproduce the current of the continuous doping profile. On the other hand, the discrete doping profile is employed without smoothing in the Poisson equation to capture the effects of the discrete dopant on the electrostatic potential.

Table. 1 shows the cut-off parameters for each doping concentration. From this, we can obtain the following equation by polynomial regression the relationship between doping concentration and Kc.

$$K_c = -0.004944073 \times (N_d)^3 + 0.6569125 \times (N_d)^2 - 28.74891 \times (N_d) + 430.6536$$

This Kc is used as a new fitting parameter for doping dependent mobility correction.

Fig.3 shows the result of applying fitting parameter to analytic doping profile. In the case of analytic doping, several arbitrary sections were divided to reflect the gradual doping change, and a fitting parameter

corresponding to the average doping concentration of each section was applied. Fig.4 means Kc extracted from the above relationship agrees well with the analytic doping profile used in general devices.

We proposed a modified doping dependent mobility model considering a wide range of doping concentrations and confirmed that the model has good agreement.

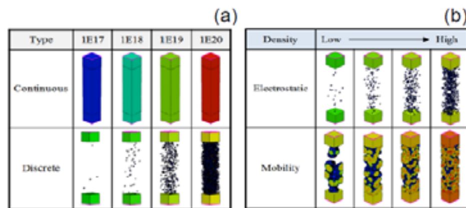

Fig.1. (a) N-type silicon resistor to compare the difference between continuous doping and discrete doping (b) Doping profiles as the input to TCAD simulation of the electrostatic potential and mobility

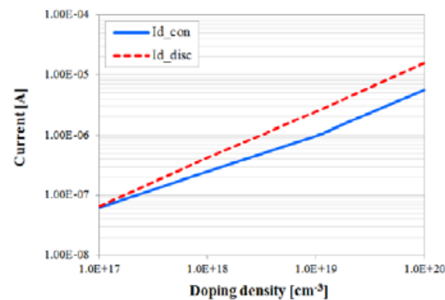

Fig. 2. Comparison of the I–V characteristics of the samples with continuous doping and discrete doping

Doping conc. [cm^{-3}]	Cut-off parameter
1.0E+17	4.170E+06
1.0E+18	5.700E+06
1.0E+19	1.132E+07
1.0E+20	2.439E+07

Table. 1. Correction cut-off parameter (K_c) for each doping concentration

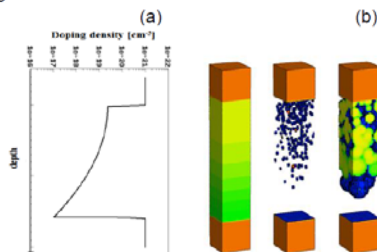

Fig.3 . (a) Doping profile in the depth direction (b) reference analytic doping *(left)*, for electrostatic *(mid)*, for mobility *(right)* doping

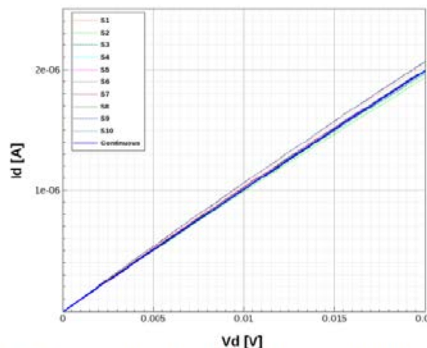

Fig. 4. I-V characteristics with newly extracted fitting parameters.

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