Three-dimensional statistical modeling of the effects of the random distribution of dopants in deep submicron MOSFETs

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Three-dimensional statistical modeling of the effects of the random distribution of dopants in deep sub-micron nMOSFETs

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The purpose of this work is to evaluate the effects of intrinsic fluctuations of the discrete distribution of dopants on the threshold voltage and on the off-state current of n-MOSFETs. A few attempts at addressing such effects have recently appeared in the literature [1-4]. However, only Refs. 3 and 4 contains a systematic statistical analysis on a three dimensional grid, limited to threshold voltage dispersion; with respect to the work by Asenov *et al.*, we use a more realistic model, taking into account the Fermi-Dirac statistics of electrons and holes, a polysilicon gate, and the effect of doping fluctuations in the polysilicon gate, source and drain. In addition, we also consider the dispersion of the off-state current, which leads to an overall increase of the standby power dissipation. We will present results obtained with definitions of the threshold voltage based on the subthreshold current and on the linear extrapolation of the input characteristics, and will compare them with analytical models and numerical 1D simulations.

Simulations are performed on statistically meaningful ensembles of devices, consisting of 200 or 1000 devices. A Monte-Carlo procedure is used to generate the discrete distribution of dopants in the active area, in the polysilicon gate, and in the drain and source diffusions, for each considered device. An efficient three-dimensional solver of the non-linear Poisson equation and a solver of the current diffusion equation have been developed and used to extract the threshold voltage and the off-state current of each device for small drain-source voltages.

With respect to Refs. 3 and 4, we find a better agreement with results obtained fom existing analytical models and from simpler 1D simulations, which take into account only doping fluctuations in the vertical direction. For example, we find that the standard deviation of the threshold voltage is proportional to $N_A^{0.25}$, where N_A is the channel acceptor doping, in agreement with most analytical models, as opposed to $N_A^{0.4}$ of [4].

Fig. 1 shows the threshold voltage frequency distribution for an n-MOSFET with an effective channel length of 100 nm, 3nm-thick gate oxide, uniform acceptor doping N_A of 10^{18} cm^{-3} in the channel, and n$^+$ poly gate ($N_D = 10^{20}$ cm^{-3}). The average threshold voltage is slightly smaller than that obtained assuming a uniform concentration of dopants (in all cases, we find a threshold voltage shift much smaller than that obtained in Ref. 3).

The frequency distribution for the off-state current is shown in Fig. 2. The dispersion of the off-state current leads to a relevant increase of the stand-by power of CMOS ICs: in this case the average off-state current is 2.46 times greater than that calculated by assuming a uniform concentration of dopants, thereby leading to an increase of the stand-by power by the same factor.

References

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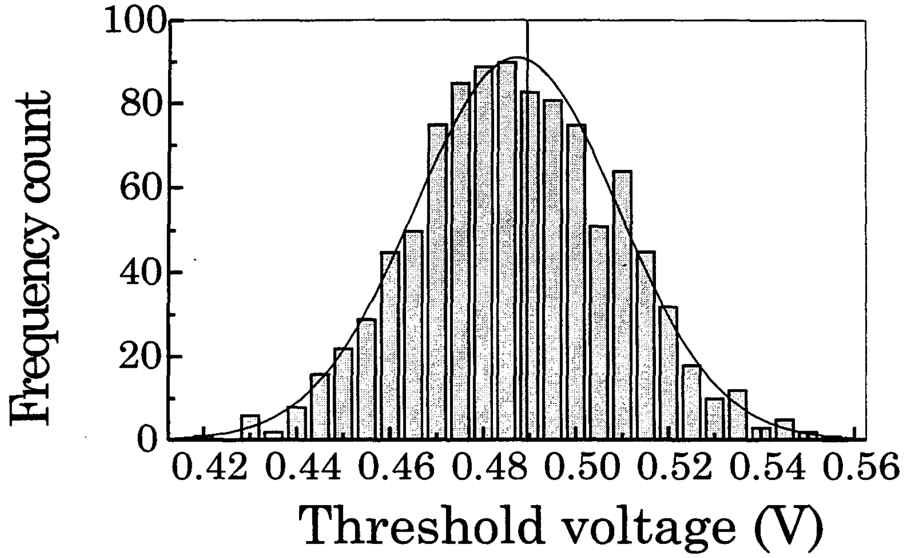

Fig. 1: Threshold voltage frequency distribution and corresponding normal distribution for a sample of 1000 NMOSFETs described in the text

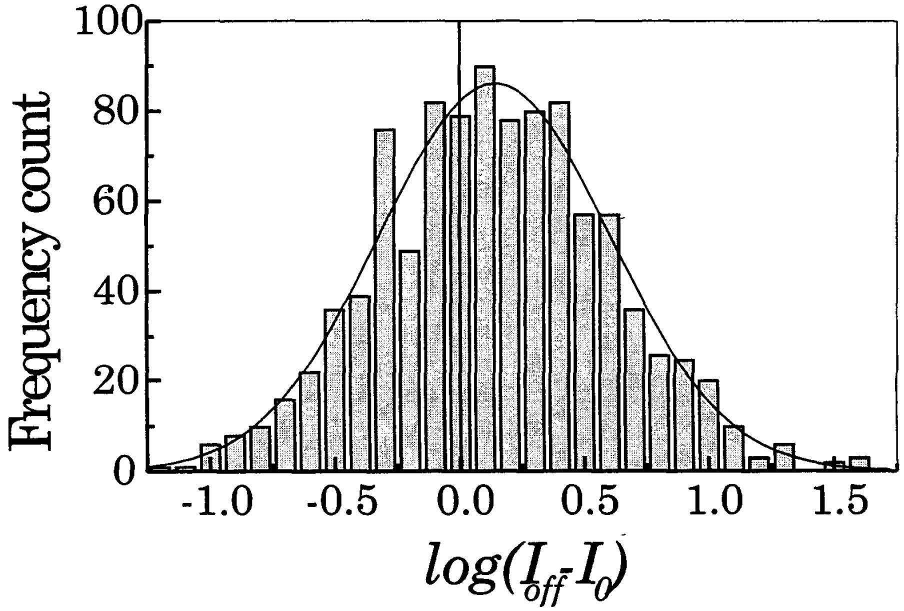

Fig. 2: Off-state current frequency distribution for a sample of 1000 NMOSFETs described in the text; on the hozintontal axis currents are represented on a logarithmic scale and are normalized over the off-state current obtained from a uniform concentration of acceptors