CHAPTER - 1

INTRODUCTION

The purpose of device modelling is to obtain the terminal characteristics of a device from its physical and process parameters, and geometrical configuration. With the passage of time, the physical structure of MOSFETs has become very complicated due to the incorporation of additional process steps to improve performance, and scaling of geometry to increase density of integration and speed. For example, a channel implantation is nowadays widely used in short-channel MOSFETs to control the threshold voltage, increase the punchthrough voltage and reduce subthreshold current. Also, with the shrinking of device dimensions, the threshold voltages of MOSFETs have become dependent on the device geometry and the drain bias. These are some of the reasons which have necessitated the use of rigorous numerical techniques to obtain the device characteristics accurately. But numerical models usually involve enormous computation time and effort, and lack in physical insight. For the simulation or analysis of LSI/VLSI circuits involving several thousand transistors, it is rather inconvenient to use numerical models at the device level as it would make the overall computation too time consuming to be practical. Hence, IC designers prefer to use analytical or empirical models, which are accurate enough for the particular application and at the same time computationally efficient. The present thesis reports the work on some new analytical models for the threshold and punchthrough voltages of small geometry MOSFETs with nonuniformly doped channels.

In Chapter 2 of this thesis, a review of the analytical models of threshold voltage, punchthrough voltage and subthreshold current of MOSFETs developed so far is presented. In the threshold voltage models, analytical methods to determine the potential and field distribution in the channel are required. For this, one must obtain the solution of Poisson's equation in the channel under the subthreshold condition. In the case of long-channel MOSFETs, a one-dimensional solution is adequate, and a closed-form expression for threshold voltage may be obtained if the channel is homogeneously doped. For short-channel MOSFETs with uniformly doped channels, two-dimensional solution of Poisson's equation has been found analytically under specific boundary conditions [52,53]. It is, however, a difficult task to find analytical solutions for the potential, and obtain a closed-form expression for the threshold voltage of MOSFETs with implanted channels, even for the long-channel case. The implanted impurity profile in the channel may be approximated by the displaced Gaussian function. In the case of boron implantation, it is more precisely represented by Pearson-IV type function [98] which is much more complicated than the Gaussian function. These functions are not integrable analytically over a finite interval, making the Poisson's equation unsolvable. Some efforts have therefore been made to obtain analytical solutions through suitable transformations of the implanted profiles. The most popular is the step profile approximation [13-18]. But this transformation is valid only for shallow implants with the peak concentration very near the silicon surface [20]. In addition, one has to use a non-physical assumption of a virtual charge-sheet in the channel for the conservation of the channel depletion width as well as the total charge in the depletion region [19,20].

In our models, the analytical difficulty to solve Poisson's equation has been removed by the use of new analytically integrable functions which fit closely with the Gaussian [26] and the Pearson-IV type distributions [30]. The construction of these functions will be discussed in detail in Chapter 3. The proposed substitute function for the Gaussian is doubly integrable over a finite interval and has a close fit with the Gaussian function over a reasonaable range. The Pearson-IV distribution function applicable to boron ions as modified in SUPREM to incorporate the effect of channeling has been simulated by constructing a function consisting of exponential terms, which is integrable analytically any number of times. The important feature of the proposed function is that it involves implantation dose and energy as its parameters.

In Chapter 4, the proposed analytically integrable functions have been used to find closed form expressions for the potential and electric field in the channel from the solution of one-dimensional Poisson's equation using the depletion approximation [26,27]. This analysis, however, yields transcendental equations to be solved numerically for obtaining the channel depletion width of long-channel MOSFETs with implanted channels. In order to derive a fully analytical model of threshold voltage, a stair-case type of doping transformation in the channel has been proposed. In this transformation, the channel region is divided into thin layers, and each layer is considered to be uniformly doped with a concentration equal to the average of the particular layer, which is easy to compute due to the integrability of the functions representing the doping profiles. Closed form expressions have been derived for the channel depletion width, the depletion layer charge, and the threshold voltage. The results obtained using our model for Gaussian doped channels as well as Pearson-IV type boron implanted channels have been compared with those obtained using numerical methods. In both cases, a very good agreement is obtained. The computation time in the proposed analytical model is at least an order of magnitude less than in the numerical model.

In Chapter 5, analytical models for short-channel MOSFETs with nonuniformly doped channels based on the charge-sharing technique [28] as well as the more rigorous two-dimensional solution of Poisson's equation have been developed [29]. The charge-sharing technique was first proposed by Yau [42] and later improved upon by Taylor [44]. It is a special geometrical technique of computing the threshold voltage of short-channel MOSFETs using the results of one-dimensional solution of Poisson's equation. In the proposed model the charge-sharing technique has been applied to nonuniformly doped channels described by the proposed analytically integrable functions. Taking into account the distorted shapes of the source and drain junction boundaries due to channel implantation, the model is able to predict the anomalous positive threshold voltage shift with decreasing channel length for heavy and deep channel implants, first experimentally observed by Nishida and Onodera [60] and analysed by Fu [59]. The accuracy of the model has been established by comparison with experimental results. More rigorous models based on two-dimensional solution of Poisson's equation have also been developed. For a MOSFET with a Gaussian doped channel, whose peak concentration is at the silicon surface, the two-dimensional Poisson's equation has been solved using the integrable function to represent the channel doping. The results obtained from the model show good agreement with experimental data. Work has also been extended to develop a two-dimensional analytical model of threshold voltage of n-channel MOSFETs with boron implanted channels, where the SUPREM simulated channel doping profiles are represented by the proposed integrable functions. The main features of the model are (a) it is purely analytical and therefore computationally faster, (b) it accepts implantation parameters such as dose and energy as its input variables rather than the implanted profile as in other two-dimensional models [64], and (c) it considers realistic source and drain junctions and channel doping profiles without hampering the analytical nature of the solution. Good agreement with experimental results validate the proposed model.

A simple analytical model for punchthrough voltage of short-channel MOSFETs with nonuniformly doped channels is presented in Chapter 6. With the rapid shrinking of MOSFET channel lengths, punchthrough effect has dominated over avalanche breakdown in controlling the maximum allowable drain voltage. Punchthrough occurs when the electric field due to drain bias sufficiently reduces the potential barrier at the source junction. The proposed model is applicable in the subthreshold region when the gate bias is more than the flat-band voltage. The model takes into account the effects of different doping and device parameters as well as the applied bias potentials. The model uses nearly exact doping profiles represented by the proposed integrable functions, instead of the step profile, which is rather inaccurate. Unlike analytical models presented earlier [44,94], this model correctly simulates the effect of substrate bias on punchthrough voltage. The results obtained from the model agree well with published experimental data.

Chapter 7 summarizes the main results of work reported in this dissertation and discusses the scope for future work. It may be concluded that a systematic effort has been made to develop computationally simple analytical models of threshold voltage of small geometry MOSFETs used in LSI/VLSI chips. In the beginning, a long-channel approximation was used, which was then extended to the short-channel case. The novelty of the proposed models lies in (a) the proposition of new integrable functions as substitute for the Gaussian and the Pearson-IV distribution functions to represent the doping profiles in the ion implanted channel, for the analytical solution of Poisson's equation, and (b) the use of a staircase doping profile approximation yielding closed-form expressions for the long-channel threshold voltage and the depletion layer charge in the channel. While the long-channel models are found to be more accurate than the existing analytical models based on the step profile approximation, the short-channel models are computationally more efficient than the numerical models and are able to predict the experimental results with good accuracy. The short-channel models have been developed in a systematic and exhaustive manner starting from a semi-empirical model based on the charge-sharing principle to rigorous analytical models based on the solution of the 2-D Poisson's equation. The first 2-D model proposed assumes a Gaussian doped channel and simplistic boundary conditions. On the other hand, the second 2-D model considers Pearson-IV type boron implanted channel and more realistic boundary conditions. The model for punchthrough voltage is also purely analytical and hence computationally faster. It successfully predicts the available experimental results.

Since the models proposed require substantially less computer time and memory than their numerical counterparts, they may play an important role in circuit simulation for VLSI design.