# Analytical Model for Phosphorus Large Angle Tilted Implantation

A. Burenkov[a], W. Bohmayr[b], J. Lorenz[a], H. Ryssel[a,c], and S. Selberherr[b]

[a]Fraunhofer-Institut für Integrierte Schaltungen,
Schottkystrasse 10, 91058 Erlangen, Germany
[b]Institute for Microelectronics, TU Vienna,
Gusshausstrasse 27-29, A-1040 Vienna, Austria
[c]Lehrstuhl für Elektronische Bauelemente, Universität Erlangen-Nürnberg,
Cauerstrasse 6, D-91058 Erlangen, Germany

Abstract

This paper describes a model for the simulation of large angle tilted implantation of phosphorus in silicon. To reduce the size of the precalculated look-up parameter table, the symmetry of the silicon crystal is exploited. Examples demonstrate the importance of ion channeling effects in LATID implantation.

## 1. Introduction

The large angle tilted implantation doping (LATID) technique provides an effective means to form the lateral dopant distributions under mask edges. A well known application of LATID is the formation of source/drain extensions in MOS transistors. Phosphorus implantation is mainly used to form the source/drain extensions of n-type LATID devices. The typical energy range is 20 to 80 keV, the dose depends on ion energy and is approximately $5 \cdot 10^{13} cm^{-2}$ or lower. Various tilt and rotation angles are used for this kind of devices. In LATID, channeling effects are more important than in other devices, because the ion beam may be oriented close to one of the main crystallographic axes. Therefore, the penetration depth and the lateral extension of the implanted profile depend on ion beam orientation relative to the silicon crystallographic directions. Since the tilt and rotation angles vary over a large range in LATID, the model for LATID implantation has to take into account several channeling directions, and not only one as in the conventional small tilt angie implantation models.

## 2. Model

In LATID application the tilt and rotation angles are defined relative to the wafer flat. Additionally for performing a simulation, the orientation of the simulation plane on the wafer and the silicon crystal orientation relative to the wafer flat must be known. These technology related parameters are used as input parameters for the suggested model. The angular variables build a relative large variety when we keep in mind that the critical

channeling angles of phosphorus in silicon are about a few degrees. This means that in order to describe the angular dependence by a look-up table, an angular grid size of a few degrees is required. Taking a homogeneous grid size of 1 to 3 degree for each of the two independent angular variables, we would get several thousand of angular points for each energy. An unacceptable large amount of Monte Carlo calculations would be required to fill such a look-up table with parameters, therefore we suggest here another approach to store and to use the orientation dependent data.

We exploit that many combinations of tilt and rotation angles are crystallographically equivalent because of the symmetry of the silicon crystal. Table 1 shows some examples of the crystallographically equivalent directions. The rotation angle is zero, when the ion beam is normal to the flat of the wafer. The ion beam is parallel to a {110} type plane of the (100) oriented silicon wafer in this case. Rotation of the wafer is performed around the normal of the silicon wafer.

Table 1 Crystallographically equivalent ion beam directions for (100) silicon

| | | | | | | |
|---|---|---|---|---|---|---|
| Tilt | 45° | 45° | 52.2° | 52.2° | 69.3° | 69.3° |
| Rotation | 15° | 75° | 18.4° | 71.6° | 4.1° | 85.9° |
| Tilt | 55° | 55° | 42.1° | 42.1° | 69.7° | 69.7° |
| Rotation | 20° | 70° | 13.9° | 76.1° | 7.3° | 82.7° |
| Tilt | 60° | 60° | 35.5° | 35.5° | 72.8° | 72.8° |
| Rotation | 25° | 65° | 14.4° | 75.6° | 13.4° | 76.6° |

All the combinations of tilt and rotation angles which build a horizontal row in the table are crystallographically equivalent for silicon. There are 6 crystallograpically equivalent directions per octant, 24 for the semi-sphere. The technologically relevant variety of tilt and rotation angles builds a semisphere, but only *1/48* of the sphere represents all non-equivalent directions. If we orient the z-axis normal to the wafer surface, this reduced sector can be defined by a spherical triangle build by the intersection of the planes $y=0$, $y=x$, and $x=z$ with the unit sphere. We define the look-up table for the implantation parameters in this reduced sector of ion impact angles. To get the ion implantation parameters for a defined direction of the ion beam we proceed as follows: For the given beam direction, the crystallographically equivalent direction out of the reduced sector of non-equivalent directions is calculated. Subsequently, a linear two-dimensional three-point interpolation in the reduced angular sector is performed for all the model parameters which depend on the ion impact direction.

It is known that ion implantation profiles depend critically on the wafer orientation only for directions close to the main crystallographic directions [100], [110], and [111], but they vary smoothly in the areas beyond the critical channeling angles relative to main axes and planes. Taking advantage of this behavior, we use an inhomogeneous look-up table for the angular dependence of the implantation parameters. More parameter definition points are located near the main channeling directions and less in the areas between the main channeling direction. Moreover, we do not predefine the values of the angular variables in the look-up table. This means that new parameter description points

can be added to the look-up table of the model without changing the code or the interface. The look-up table stored in an external file can be extended when new values for implantation parameters become available from Monte Carlo calculations or from experiments. To calculate the implantation distributions analytically, advanced models with the depth dependent lateral scattering [1] have been used. The vertical as well as the lateral distributions were approximated by Pearson distributions. The orientation dependent ion implantation parameters required for the analytical model were calculated with the Monte Carlo module MCIMPL of the VISTA framework [2].

## 3. Results

Figure 1 shows depth profiles of phosphorus implanted with an energy of 12keV into (100) silicon. The implantation dose per unit area normal to the ion beam amounted to $10^{14}cm^{-2}$. The profiles shown were calculated with different appoaches: crystalline based Monte Carlo [2] method, amorphous material analytic model [1], and using the model suggested in this paper. First, we should mention the large difference between the predictions of the crystalline based Monte Carlo calculation and the amorphous material model. The penetration depth at the $10^{16}cm^{-3}$ concentration level predicted by the amorphous material model is approximately 4 times smaller as the one calculated for crystalline silicon. This difference is due to strong channeling at low energies even for ion beam directions which deviate from the main channeling directions. In fact, the 7° tilt does not help to avoid channeling at these low energies, therefore only models which are based on a crystalline material appoach are capable to describe the deep penetration of impurities at low energies typical for modern MOS technology. The crystalline material based analytic model of this work satisfactorily reproduces the Monte Carlo profiles and is, therefore, able to predict the deep penetration of the ions associated with channeling. The difference between the profiles calculated at 7° and 45° with the new model is caused by two main factors: different ion beam impact directions and different point response distributions as a result of channeling. Figure 2 elucidates the effect of the point response modification in dependence of the ion impact direction. The figure shows different one-dimensional profiles of phosphorus (50 keV, $10^{13}cm^{-2}$), all implanted with the same tilt angle of 45° , but with different rotation angles. In amorphous material, the implantation profile would show no dependence on the rotation angle, since there is no orientation dependence of the point response function in amorphous material. With the new model, we observe a rather strong dependence on the rotation angle. At 0°, the ion beam direction coincides with the {110} plane of silicon, rotation of 9° does not correspond to any major channeling directions, and 36° is again close to the <110> axis and to the {100} type plane of the

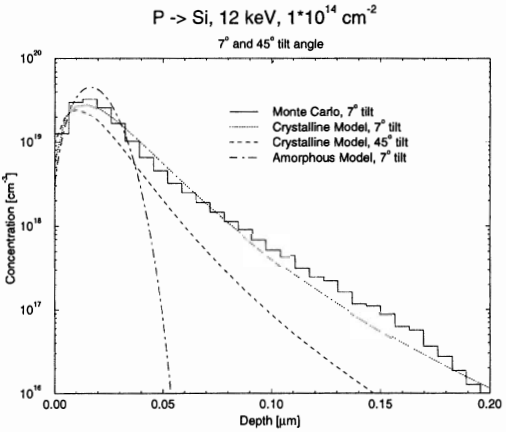


Fig. 1: Depth profiles of phosphorus ions

silicon. Figure 3 shows a two-dimensional post-implantation distribution of phosphorus in a test LATID structure simulated with the analytical model. The structure consists of a (100) silicon substrate and a polysilicon mask with a bevelled edge. The phosphorus ion beam was tilted counter-clockwise by 45° and rotated by 67° relative to the simulation plane. The implantation energy and dose are 20 keV and $5 \cdot 10^{13} cm^{-2}$, respectively. The simulation plane is parallel to the (100)-type plane of the silicon crystal. Concentration lines from $10^{17}$ to $10^{19} cm^{-3}$ are shown for the standard (solid line) and for the new (dotted line) model. The new crystalline based model predicts larger penetration depths as compared to conventional amorphous material based models and is sensitive to the ion beam impact direction.

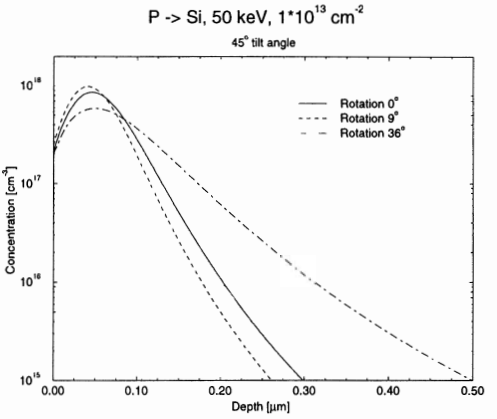


Fig. 2: Effect of rotation angle

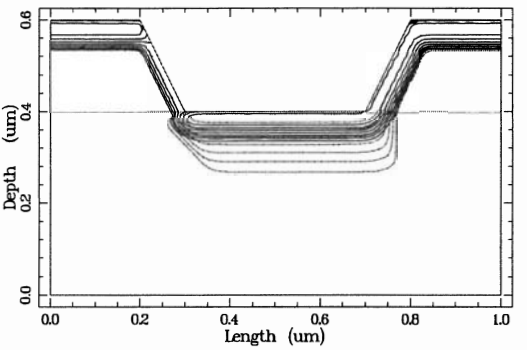


Fig. 3: Two-dimensional distributions of phosphorus in a LATID structure

## 4. Acknowledgement

This work was carried out in cooperation between ADEQUAT (JESSI project BT11) and PROMPT (JESSI project BT8B) and has been funded by the EU as ESPRIT projects No. 8002 and 8150, respectively.

## References

[1] J. Lorenz, C. Hill, H. Jaouen, C. Lombardi, C. Lyden, K. de Meyer, J. Pelka, A. Poncet, M. Rudan, S. Solmi, *The STORM Technology CAD System*, Proceedings of the International Workshop on TCAD Systems (eds F. Fasching, S. Halama, and S. Selberherr), Springer Verlag, Wien, pp. 163-196, 1993.

[2] H. Stippel and S. Selberherr, *Three Dimensional Monte Carlo Simulation of Ion Implantation with Octree Based Point Location,* IEICE Transactions on Electronics, Vol. E77-C, No. 2, pp. 118-123, 1994.