Very brief Introduction to Ion Implantation for Semiconductor Manufacturing

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Abstract

The key feature of semiconductors, that makes them so successful in modern electronic devices, is the possibility to alter their conductivity several orders of magnitude by introducing small quantities of dopant atoms.

Ion implantation is the method of choice in state of the art semiconductor manufacturing to bring the dopants into the substrate material, mainly due to its ability to accurately control the number of implanted dopants and and to place them at the desired depth.

Ion implantation works by ionizing the required atoms, accelerating them in an electric field, select only the species of interest by an analyzing magnet and direct this beam towards the substrate. When entering the substrate material the energy of the dopants decreases, while they interact with the target material. After some time the atoms come to rest at some depth depending on their initial energy. This depth has some distribution as the collisions with the target atoms are random.

So one important point for the device design is to know which initial energy is necessary to place the dopants at the required depth and what will be their spread. Several methods and theories exist to answer this question. Within this text expecially the LSS (Lindhard, Scharff, Schiøtt) theory is briefly reviewed as a background for the *SIMPIMPLANT* program which allows to draw one-dimensional distributions of the typical dopants in silicon technology.

Contents

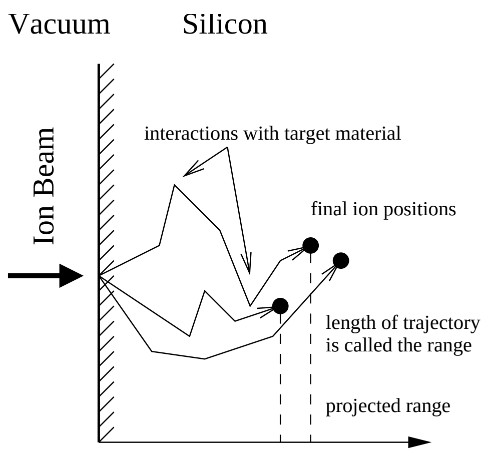

Figure 1: Range R and projected Range R_p

1 Introduction

Ion implantation replaced chemical (diffusion) doping for nearly all applications in todays silicon technology. A huge number of papers and books is available which treats the various aspects of ion implantation ranging from impurity profiles over crystal damage and annealing to equipment design. This brief text is not intended to give you a full coverage, even not an overview, it is just considered to accompany a small program written in Ruby [1] called *SIMPIMPLANT*[2] that allows to draw one dimensional doping profiles, using gaussian distributions, based on the LSS theory. Therefore the focus is put on simple range theory. Excellent introductory texts which give you an overview with further references on the topic are [3] and [4].

2 Some Definitions

The two key parameters defining the final implant profile are dose Φ (usually given in $atoms/cm^2$) and energy E (in keV). The dose is related to the beam current I by the following formula:

$$\Phi = \frac{It}{q_i A}, \tag{1}$$

were t denotes implantation time, A beam area and q_i is the charge per ion. Typical beam currents and implantation doses range from $1\mu A - 30mA$ and $10^{11} - 10^{16} atoms/cm^2$. The lowest energies used start at the sub keV area for ultrashallow junctions to the MeV range for deep wells.

When the ions enter the substrate they continously loose energy and change direction by collisions with the target atoms (see also fig. 1). Due to the random nature of the collisions the total distance travelled (range) and its projection on the direction parallel to the ion beam (projected range) are random variables. R_p denotes the *projected range*, the depth were most ions stop. The *projected straggle* ΔR_p describes the statistical fluctuation of R_p.

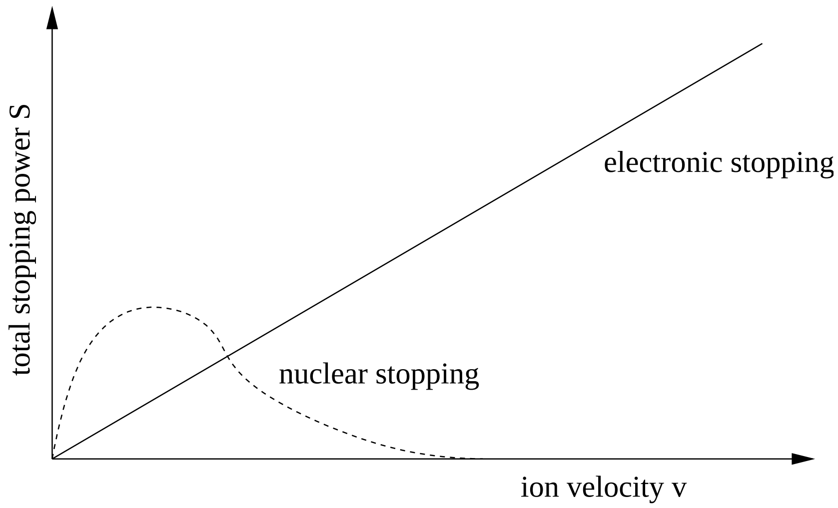

Figure 2: Range R and projected Range R_p

3 Ion Stopping

When the implanted ion enters the target material there are two main effects that causes an energy loss:

- elastic collisions with the nuclei of the target material
- and inelastic colllisions with the electrons.

Means the *total stopping power* S defined as the energy loss per unit path length of the ion can be defined as:

$$S = \left(\frac{dE}{dx}\right)_{\text{nuclear}} + \left(\frac{dE}{dx}\right)_{\text{electronic}}. \tag{2}$$

From fig. 2 it can be seen that at low ion velocities nuclear stopping dominates, whereas at higher velocities the energy is transfered to the electrons of the target material.

4 Impurity Profiles

Based on the LSS theory the implant profile (projected ranges R_p of a huge number of ions) in an amorphous material can be described by a gaussian distribution due to the statistical nature of the ion stopping process.

$$n(x) = n_0 \exp\left(\frac{-(x-R_p)^2}{2\Delta R_p{}^2}\right), \quad \text{with} \quad n_0 = \frac{\Phi}{\sqrt{2\pi}\Delta R_p} \tag{3}$$

The profile is defined by the implanted dose Φ, the projected range R_p and the projected straggle ΔR_p. R_p and ΔR_p are tabulated for various materials and dopants relevant in silicon technology in e. g. [3]. Of course they also depend on the implant energy E.

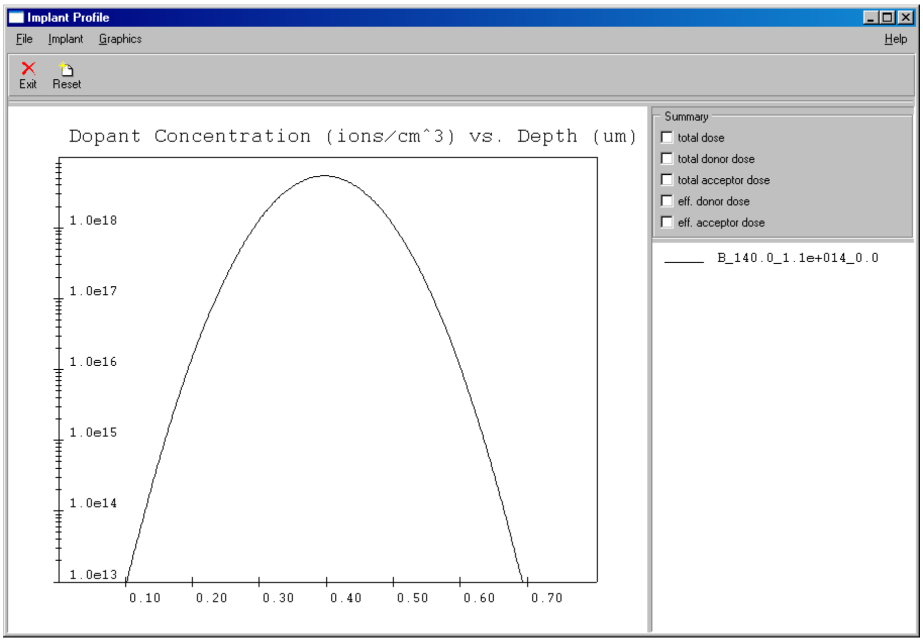

Figure 3: implant profile by SIMPIMPLANT

In real applications many times the implantation is done through composite layers of different materials. In this case a simple approximation of the implant profile can be calculated as follows:

- Convert all individual layer thicknesses t_i to equivalent silicon thickness by:

$$t_{eqSi} = t_i \, \frac{R_{p_{Si}}}{R_{p_i}} \tag{4}$$

- Calculate the implant profile in silicon and scale it back using the transformation above.

The described procedure yields continous, but abrupt changing profiles which are no real, but usable as first approximations (fig. 4).

5 A brief Userguide to SIMPIMPLANT

SIMPLANT has a simple GUI and should be rather intuitive to use. Fig. 5 shows the necessary inputs to add a new implant, the meaning of dose, energy and species might be clear (hopefully) after the explanations given so far. Tilt is another parameter, where the beam is not perpendicular to the surface to achieve specific 3d structures. As we are only interested in one-dimensional profiles, for tilted implants only the vertical and not the lateral component is considered.

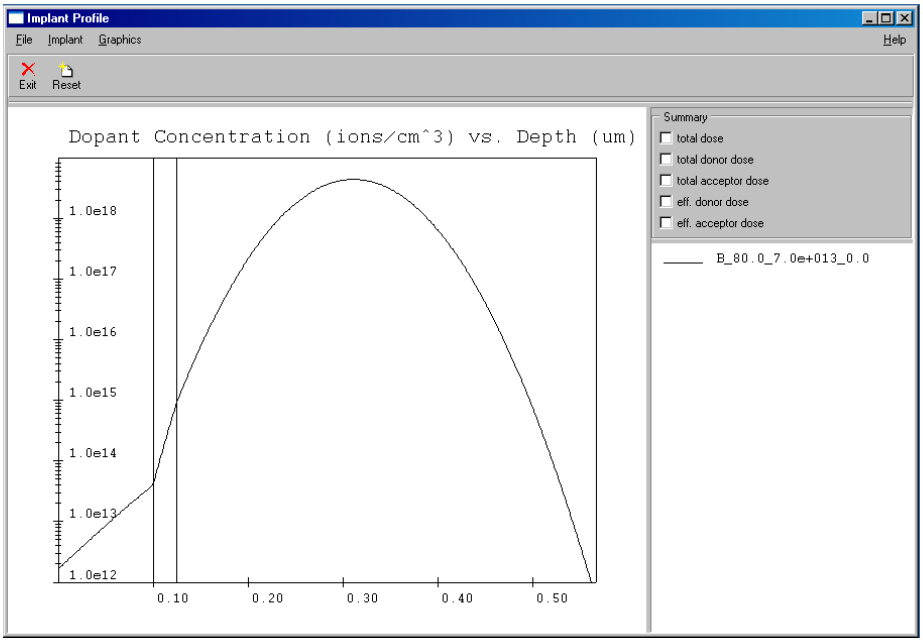

Figure 4: implant in composite structure by SIMPIMPLANT

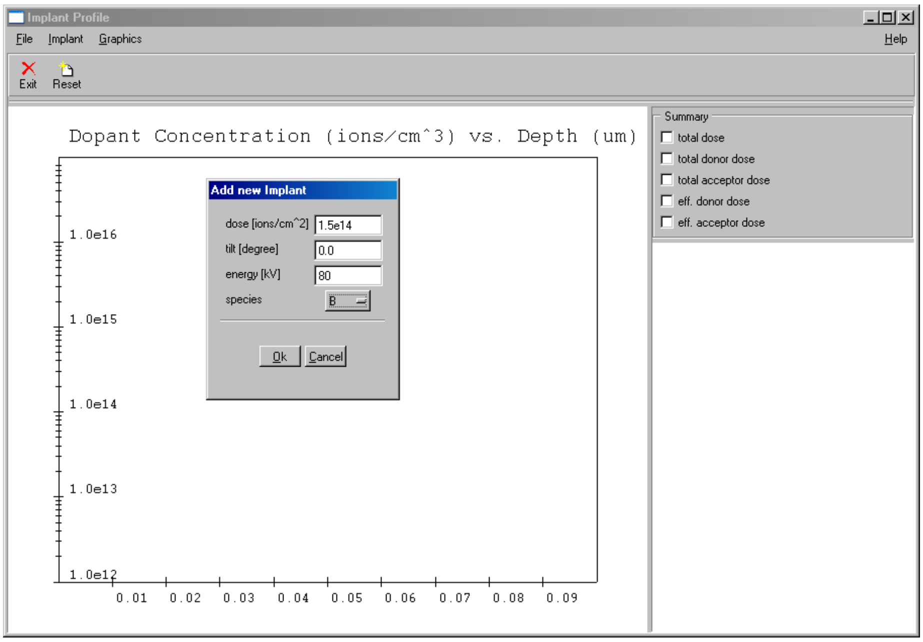

Figure 5: dialog for adding an implant

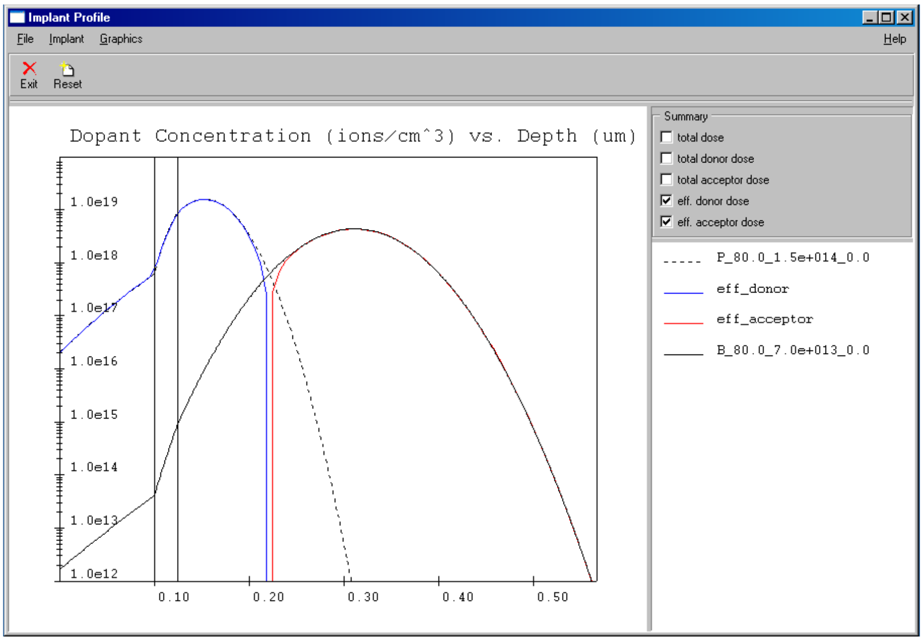

Figure 6: overlaid implants

6 Summary

The small Ruby application *SIMPIMPLANT* is intended as a simple utility for persons working in silicon semiconductor processing, who need a quick zero order estimate about dopant profiles for usual implants. But first of all the program was written to give the author some experience in Ruby.

SIMPIMPLANT is available under the LGPL (see file license.txt).

References

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[3] S. M. Sze. *VLSI Technology*. McGraw Hill, second edition, 1988. 2, 3

[4] Stanley Wolf and Richard N. Tauber. *Silicon Processing for the VLSI Era Volume 1 - Process Technology*. Lattice Press, second edition, 2000. 2