EE143 **N. Cheung**

Ion Implantation Profile and Range Data

In EE143, we use a gaussian function to approximate the ion implantation concentration depth profile:

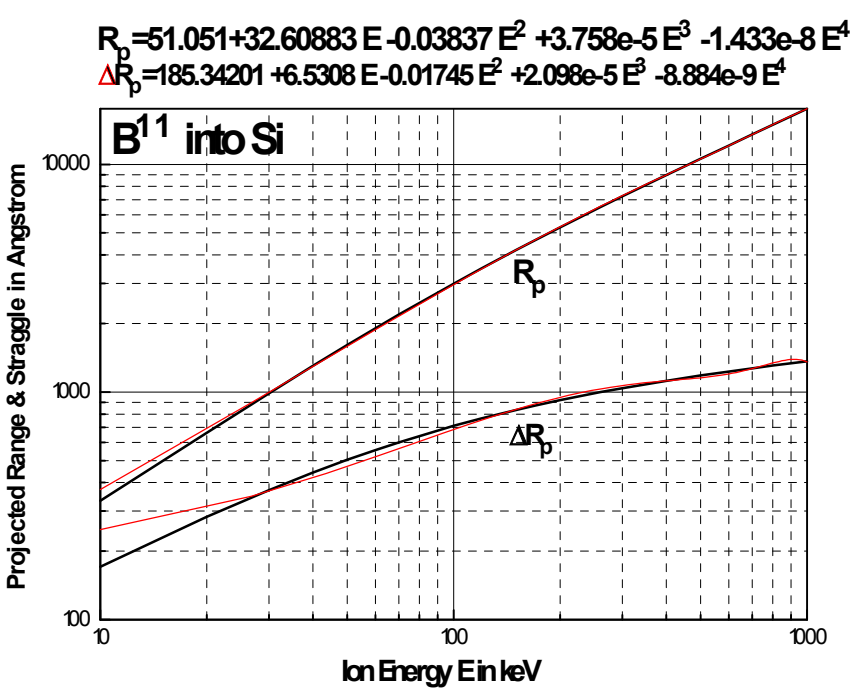
$$C(x) = \frac{\phi}{\sqrt{2\pi}\,\Delta R_p} \exp\left[\frac{-(x - R_p)^2}{2\Delta R_p^{\,2}} \right]$$

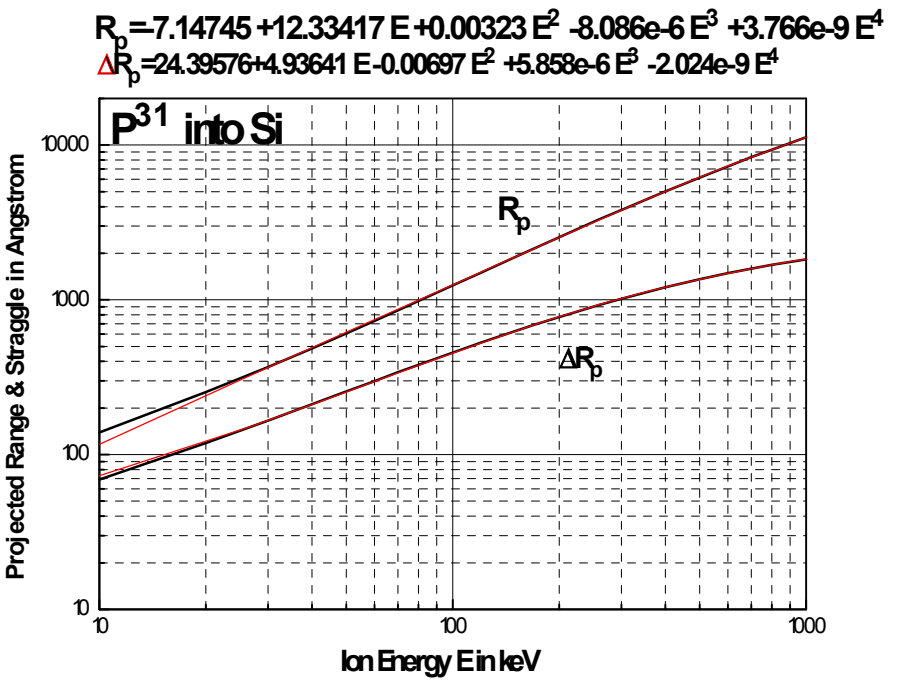
where ϕ is the implantation dose (in # /cm^2), R_p is the projected range and ΔR_p is the longitudinal straggle. This gaussian approximation is reasonably good for sheet resistance calculations because the integral quantity R_s ($\approx \frac{1}{q\mu\phi}$) is less sensitive to details of the distribution. However, the gaussian function has too rapid a decay with distances from R_p and can lead to smaller calculated junction depths x_j .

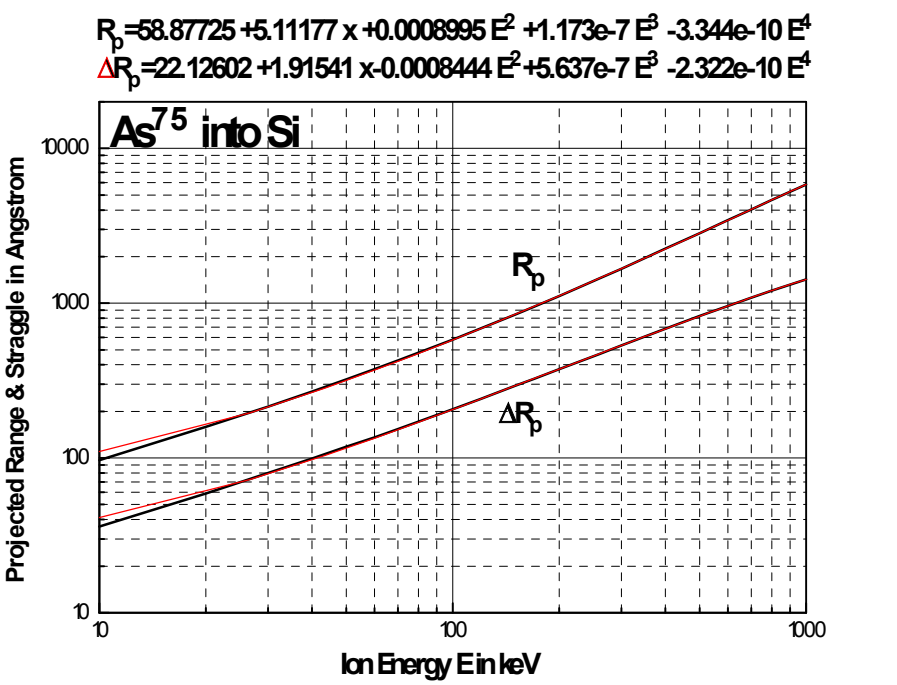
The rationales to choose the gaussian approximation are: (1) only two parameters (R_p and ΔR_p) are used to describe the shape of the depth profile; (2) the gaussian function is a natural solution of the diffusion equation, which we have to deal with when further annealing steps are encountered after implantation. A better approximation for the implantation profile is the Pearson-IV distribution which requires the first four spatial moments of the distribution but such calculations will require numerical procedures [see more advanced texts such as Plummer et al].

Projected Range R_p and Longitudinal Straggle ΔR_p for common dopants used in IC technology, B, P and As implanted into Si are shown in the following graphs (solid lines). The ranges (in Å) are also fitted to a polynomial (dashed lines) of the form:

$$a0+a1*E+a2*E^2+a3*E^3+a4*E^4 \qquad \text{with E in keV}$$



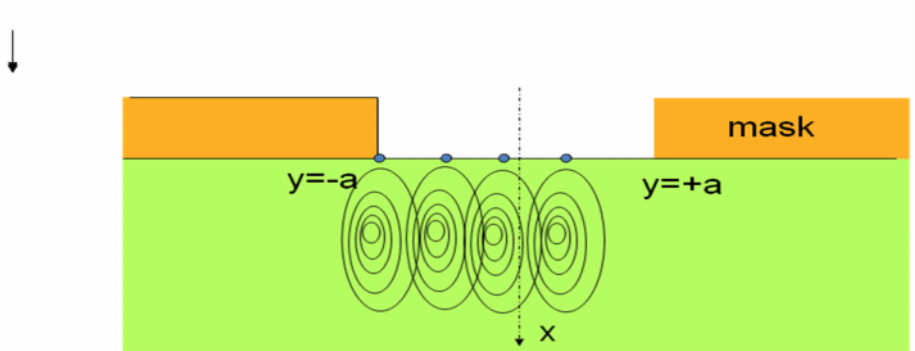




Transverse straggle ΔR_t

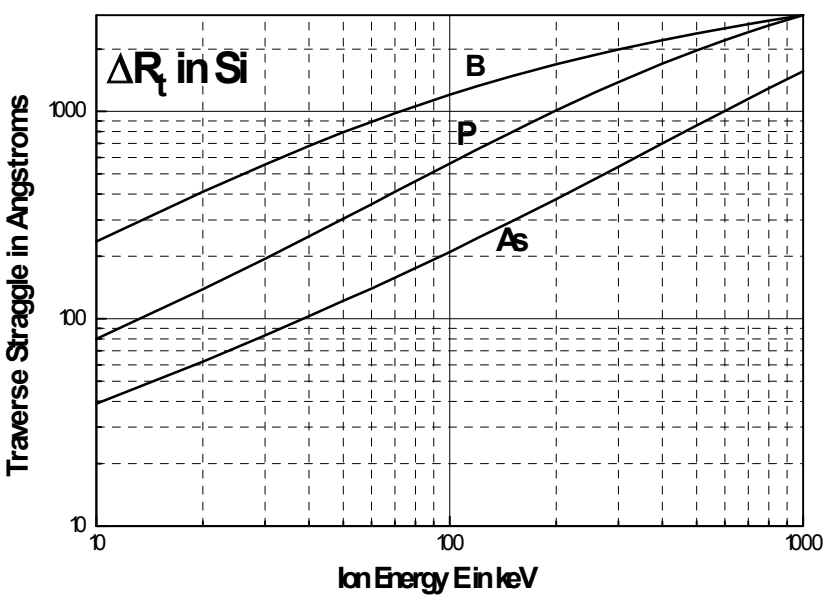
For common energies used in IC production (<200 keV), the transverse straggle (ΔR_t) is always larger than the longitudinal straggle (ΔR_p). The ΔR_t values for B, P, and As are also attached for your reference.

For a line-shape mask opening of width 2a , the 2-D implantation profile is approximated by :



$$C(x,y) = \frac{\phi}{\sqrt{2\pi}\,\Delta R_p} \exp\left[\frac{-(x-R_p)^2}{2\Delta R_p^2}\right] \bullet \frac{1}{2}\left[\operatorname{erfc}\left(\frac{y-a}{\sqrt{2}\Delta R_t}\right) - \operatorname{erfc}\left(\frac{y+a}{\sqrt{2}\Delta R_t}\right)\right]$$

Note that for an infinite opening (i.e., $a \to \infty$), C(x, y) reduces to the one-dimensional case $C(x) = \frac{\phi}{\sqrt{2\pi}\,\Delta R_p} \exp\left[\frac{-(x-R_p)^2}{2\Delta R_p^2}\right]$, as expected.



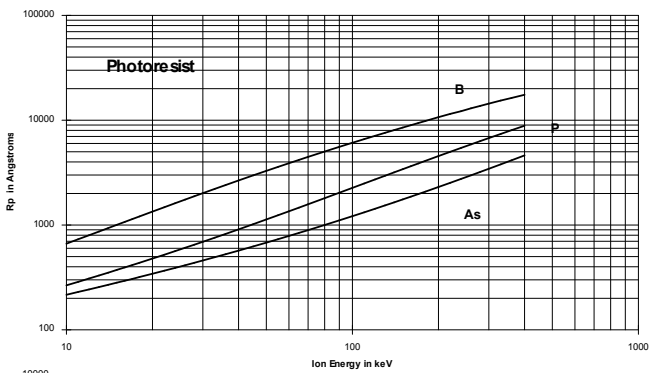
Ion Channeling

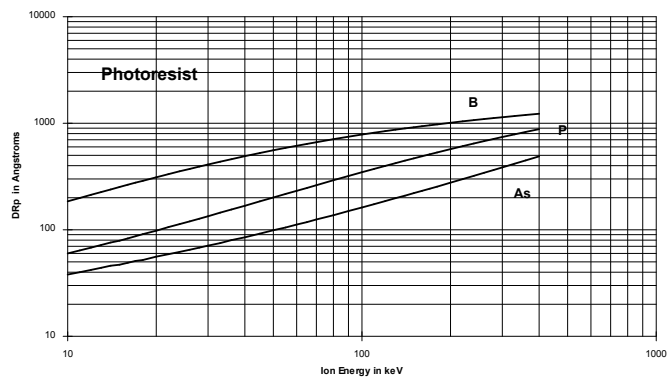
To minimize ion channeling effect, the Si substrate is usually tilted by 7° with respect to the ion beam but the cos 7° correction to projected depths is close to unity (~0.993) and is usually neglected in calculations.

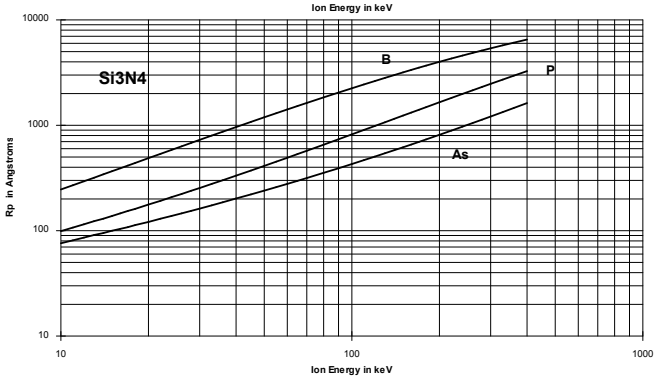
Implantation into other Substrates

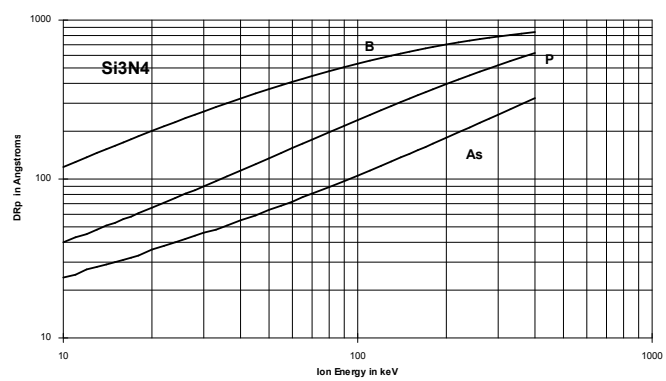
Poly-Si is pure Si, so it has identical ranges as single-crystal Si. Range in SiO_2 is about several percent smaller than that of Si. For IC processing designs, we are primary concerned with the dopant profile in Si. When we deal with problems involving implantation through SiO_2 into Si, we usually treat the SiO_2 having the same energy stopping power as Si to *simplify* the calculations. Detailed profile data of ions in many substrates can be found in tables published by Gibbons et al or from Monte Carlo Simulators such as SRIM. [**http://www.srim.org/index.htm]**

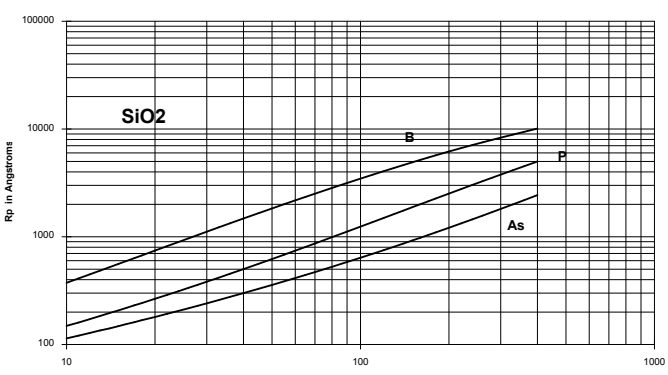
The following six plots show simulated values of R_p and ΔR_p by SRIM for B, P and As into Photoresist, Si_3N_4 and SiO_2.

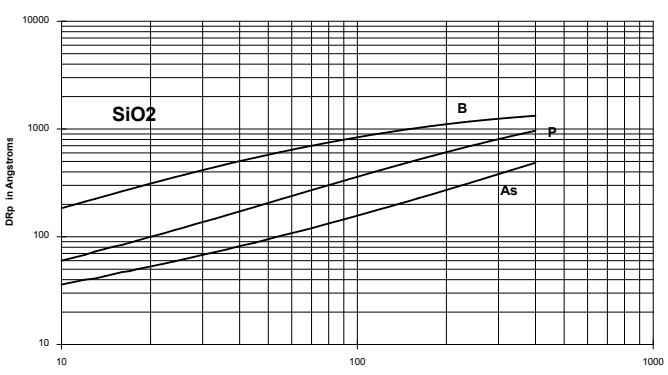






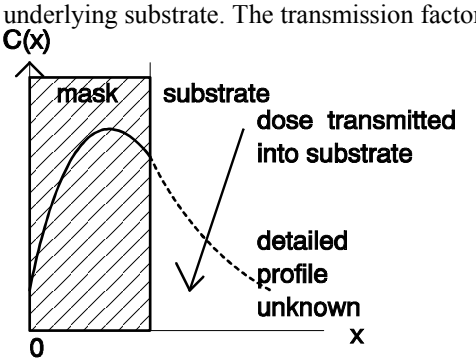






Implantation profiles through multilayer structures

The profile calculations generally require advanced techniques such as Boltzmann transport equation or Monte Carlo simulation. For implant masking calculations, most times we only care about the fraction of implant dose not passing through the mask thickness, not the detailed depth profile into the underlying substrate. The transmission factor T is equal to:



$$T = \frac{\phi_{transmission}}{\phi} = \frac{1}{2}\,\mathrm{erfc}\left[\frac{d - R_p}{\sqrt{2}\,\Delta R_p}\right]$$

where d is the mask thickness, R_p and δR_p correspond to values of the ion through the **mask** material, and $\phi_{transmission}$ is the dose of ions that penetrate pass through the mask. The complementary error function erfc(x) is plotted in Figure 4.4 of Jaeger.

***Example*:.**

SiO_2 is used as the implantation mask and we ***assume*** the SiO_2 stopping power is identical to that of Si. For 200 keV Boron, find the required oxide thickness d such that the transmission factor $T = \frac{1}{2}\,\mathrm{erfc}\left[\frac{d - R_p}{\sqrt{2}\,\Delta R_p}\right]$ is: (i) 10^{-5} , (ii) 10^{-4}, and (iii) 10^{-3}.

Transmitted fraction $\frac{\phi_f}{\phi} = \frac{1}{2}\mathrm{erfc}(z)$ where $z = \frac{d - R_p}{\sqrt{2}\Delta R_p}$

(i) $\frac{\phi_f}{\phi} = 10^{-5} \Rightarrow z = \mathrm{erfc}^{-1}(2 \times 10^{-5}) = 3.02$

(ii) $\frac{\phi_f}{\phi} = 10^{-4} \Rightarrow z = \mathrm{erfc}^{-1}(2 \times 10^{-4}) = 2.64$

(iii) $\Rightarrow \frac{\phi_f}{\phi} = 10^{-3} \Rightarrow z = \mathrm{erfc}^{-1}(2 \times 10^{-3}) = 2.20$

$\therefore$ d values are :

(i) $= \sqrt{2}\Delta R_p \bullet z + R_p = \sqrt{2} \times 0.093 \times 3.02 + 0.53 = 0.93\ \mu m$

(ii) $= \sqrt{2} \times 0.093 \times 2.64 + 0.53 = 0.877\ \mu m$

(iii) $= \sqrt{2} \times 0.093 \times 2.20 + 0.53 = 0.82\ \mu m$

Si_3N_4 is more effective than SiO_2 in blocking implantation by about 15%. Since we use the photoresist as an implantation mask, they are usually made sufficiently thick to completely block the implanted dopants. For this reason, the ranges of dopants into photoresist are not given here but they can be looked up in tables. Roughly, a photoresist layer should be 1.8 times the thickness of a SiO_2 blocking layer. The rule-of-thumb to achieve sufficient blocking is to have the masking layer thickness larger than $R_p + 5\Delta R_p$ of that ion into the masking material.

What happen to charges carried by the ions ?

One common question asked is the charge state of the ions once they enter the solid. The answer is positive ions will be neutralized by electrons in the solid instantaneously (e.g. Si) or after annealing steps (e.g. thick SiO_2). We need the positive charge on the ions so that we can manipulate the accelerating energy. In principle, any particle with positive charge, negative charge, or in the neutral state will give the same implantation profile provided they have identical kinetic energy.