

UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Electrical Engineering and Computer Sciences

EE143 Midterm Exam #1

Family Name _____ First name _____ SID _____

Signature _____ **Solutions** _____

Make sure the exam paper has 7 pages (including cover page) + 3 pages of data for reference

Instructions: DO ALL WORK ON EXAM PAGES

This is a 90-minute exam (2 sheets of HANDWRITTEN notes allowed)

Grading:

- **The reader can only assess what you put down on the exam paper, not what is inside your brain. Please be concise with your answers. For answers requiring explanation, adding sketches can be very effective.**
- **To obtain full credit, show correct units and algebraic sign. Numerical answers orders of magnitude off will receive no partial credit.**

Problem 1 (20 points) _____

Problem 2 (20 points) _____

Problem 3 (20 points) _____

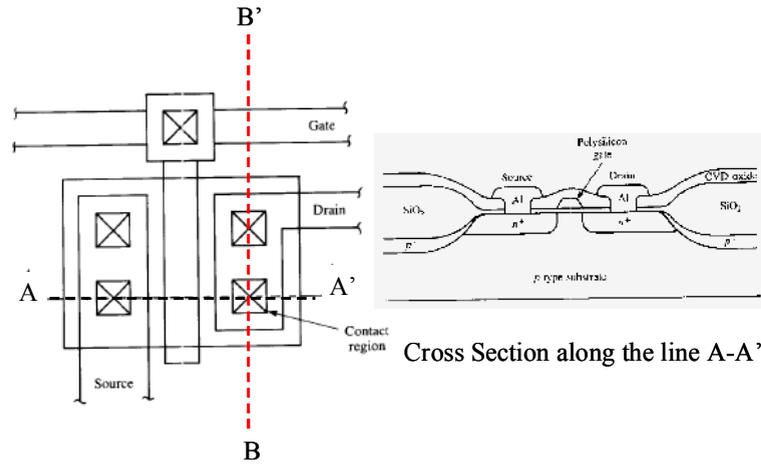
Problem 4 (20 points) _____

Problem 5 (20 points) _____

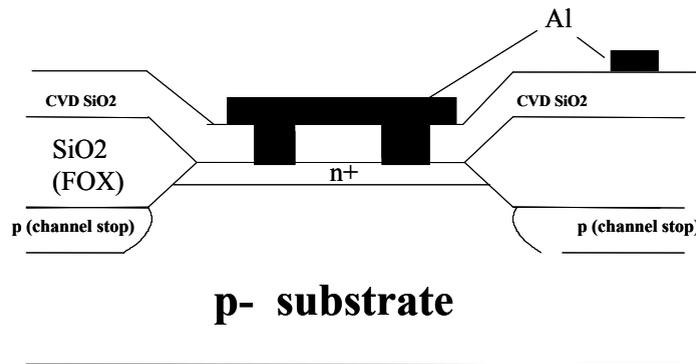
TOTAL (100 points) _____

Problem 1 Simple Process Flow (20 points total)

Figures below (taken from your Jaeger textbook and homework) show the top view and cross-section of a MOSFET along the line A-A'.



- (a) (7 points) Sketch the cross-section of the device along the line B-B'. Label all important features of the cross-section.



- (b) (5 points) The process starts with a p-type Si wafer. List **ALL** thermal oxidation steps and their purpose in this process sequence.

1. Pad oxide – relief thermal stress between Si and silicon nitride during field oxidation
2. Field oxidation – form isolation between devices
3. Gate oxidation – gate dielectric for MOSFET.

- (c) (5 points) The process starts with a p-type Si wafer. List **ALL** ion implantation steps and their purpose in this process sequence.

1. Channel stop implant – raise threshold voltage under field oxide
2. Source/Drain implant – form MOSFET source and drain.
[Optional- threshold voltage tailoring of MOSFET]

- (d) (3 points) In this process flow, which step has the highest thermal budget for dopant diffusion? Briefly state your reasoning.

Field oxidation, high temperature and long time to grow ~ 0.5-1 um of oxide

Problem2 Ion Implantation (20 points total)

(a) (i) (5 points) 1000 keV boron was implanted into n-type Si ($N_B = 10^{15}/\text{cm}^3$) to a dose of $10^{15}/\text{cm}^2$. What are the junction depths?

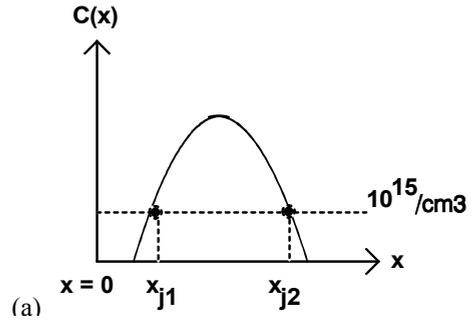
$$R_p = 1.756 \mu\text{m} ; \Delta R_p = 0.1364 \mu\text{m}$$

$$\therefore \frac{10^{15}/\text{cm}^2}{\sqrt{2\pi} \cdot (0.1364 \times 10^{-4}) \text{cm}} \exp\left(-\frac{(x_j - R_p)^2}{2(\Delta R_p)^2}\right) = 10^{15}/\text{cm}^3$$

$$\therefore (x_j - R_p)^2 = 10.286 \times 2(\Delta R_p)^2$$

$$\therefore x_{j1} = 1.756 - 0.62 = \mathbf{1.13 \mu\text{m}}$$

$$x_{j2} = 1.756 + 0.62 = \mathbf{2.37 \mu\text{m}}$$



(ii)(5 points) Using the approximate formula for sheet resistance: $R_s = 1 / (q \mu \phi)$, what is the sheet resistance of the implanted layer ?

$$\text{Peak concentration } N_p = \frac{10^{15}/\text{cm}^2}{\sqrt{2\pi} \sqrt{(\Delta R_p)^2 + 2Dt}} \approx 10^{19}/\text{cm}^3$$

$$\therefore \mu \text{ (p-layer)} \approx 40 \text{ cm}^2/\text{V-sec} \quad \therefore R_s = \frac{1}{1.6 \times 10^{-19} \times 10^{15} \times 40} \approx \mathbf{160 \Omega/\text{square}}$$

(b) (5 points) Explain why we need an additional annealing step at $\sim 900\text{C}$ after implantation of dopants.

- 1) Restore damaged Si caused by ion bombardment to single crystal Si.
- 2) Place implanted dopants at crystalline sites of Si lattice so that the dopants give "shallow" donor or acceptor energy levels [i.e. ,dopant activation]

(c) (5 points) We would like to form ultra-shallow junctions, discuss two methods used in IC processing to minimize the ion channeling effect

- 1) Tilt the Si wafer surface by about 7 degrees with respect to beam incidence direction plus wafer rotation to avoid axial and planar channeling
- 2) Preamorphise the Si substrate first by Si implantation, followed by dopant implantation.

Problem 3 Quick Calculations (20 points)

(a) (10 points) For a particular oxidation process, it is known that the oxidation **rate** (dx_{ox}/dt) is $0.24 \mu\text{m}/\text{hour}$ when the oxide thickness is $0.5 \mu\text{m}$ and it becomes $0.133 \mu\text{m}/\text{hour}$ when the oxide thickness is $1 \mu\text{m}$. Find the linear oxidation constant (B/A) and the parabolic oxidation constant B . Give answers in proper units.

From the Grove model, we have : $x_{ox}^2 + Ax_{ox} = B(t+\tau)$

Therefore,

$$2x_{ox} \frac{dx_{ox}}{dt} + A \frac{dx_{ox}}{dt} = B$$

$$\text{or } \frac{dx_{ox}}{dt} = \frac{B}{A+2x_{ox}}$$

From $0.24 = \frac{B}{A+0.5 \times 2}$ and $0.133 = \frac{B}{A+1 \times 2}$, we get

$A=0.25 \mu\text{m}$, $B=0.3 \mu\text{m}^2/\text{hour}$ and $B/A = 1.2 \mu\text{m}/\text{hour}$

(b) (5 points) For a particular lithography process based on projection printing, the minimum resolution (l_m) is $1 \mu\text{m}$ and the depth of focus (DOF) is $1 \mu\text{m}$. By placing a smaller aperture over the projection lens, the numerical aperture (NA) is reduced by a factor of 2, calculate the new values of l_m and DOF.

$l_m \propto \lambda/NA$. NA reduces by 2X, $l_m = 1 \mu\text{m} \times 2 = 2 \mu\text{m}$

$DOF \propto \lambda/NA^2$. NA reduces by 2X, $DOF = 1 \mu\text{m} \times 4 = 4 \mu\text{m}$

(c) (5 points) Diffusion Predeposition of Arsenic is used to form a shallow junction in p-type Si ($N_B = 1 \times 10^{15}/\text{cm}^3$). The solid solubility of As in Si is known to be $1 \times 10^{21}/\text{cm}^3$. If the allowed junction depth is less than $0.1 \mu\text{m}$, what is the lowest sheet resistance which can be achieved?

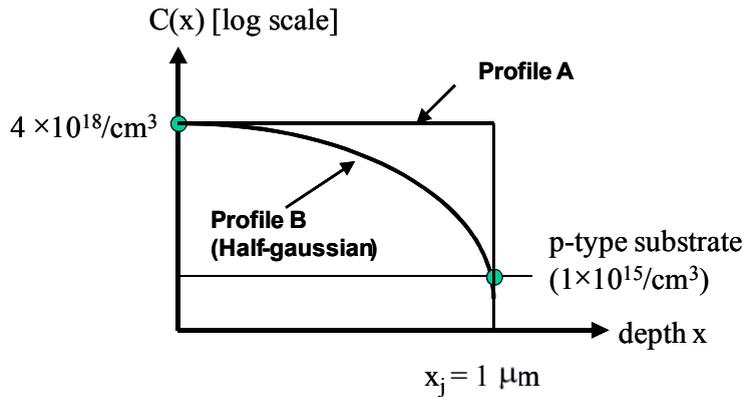
Using the n-type erfc Irvin Curves and with $N_B = 1 \times 10^{15}/\text{cm}^3$, $N_o = 1 \times 10^{21}/\text{cm}^3$,

$R_s \bullet x_j = 10 \text{ ohm-}\mu\text{m}$.

If the allowed junction depth is less than $0.1 \mu\text{m}$, the sheet resistance R_s is $> 100 \text{ ohm/square}$.

Problem 4 Dopant profiles (20 points total)

Consider the following **Arsenic** doping profiles .



(a) (5 points) Calculate the sheet resistance of **Profile A** use the mobility curves.

$$R_s = \frac{1}{q \cdot \mu_n \cdot C \cdot x_j} = \frac{1}{1.6 \times 10^{-19} \cdot 160 \cdot 4 \times 10^{18} \cdot 1 \times 10^{-4}} = 97 \text{ ohm/square}$$

(b) (5 points) Use the Irvin's curves to find the sheet resistance of **Profile B**.

$C(x=0) = 4 \times 10^{18} \text{ /cm}^3$, $N_B = 10^{15} \text{ /cm}^3$ implies $R_s x_j = 300 \text{ ohm-}\mu\text{m}$ from n-gaussian Irvin's curve

Therefore $R_s = 300 \text{ ohm-}\mu\text{m} / 1 \text{ }\mu\text{m} = 300 \text{ ohm/square}$

(c) Suppose **Profile B** is subjected to an additional drive-in diffusion step such that the (Dt) product of the half-gaussian profile is doubled.

(i) (5 points) Calculate the new surface concentration.

$$C(x=0) = \frac{Q}{\sqrt{\pi Dt}} \text{ and dose } Q \text{ is conserved with drive-in diffusion}$$

$$\text{After drive-in, } C(x=0) = \frac{4 \times 10^{18}}{\sqrt{2}} = 2.8 \times 10^{18} \text{ /cm}^3$$

(ii) (5 points) Explain concisely why the sheet resistance of profile B is lower after the additional drive-in step.

Dose Q is conserved but concentration is lower at all depths. The corresponding carrier **mobility and hence conductivity is higher** for all depths Therefore sheet resistance is lower.

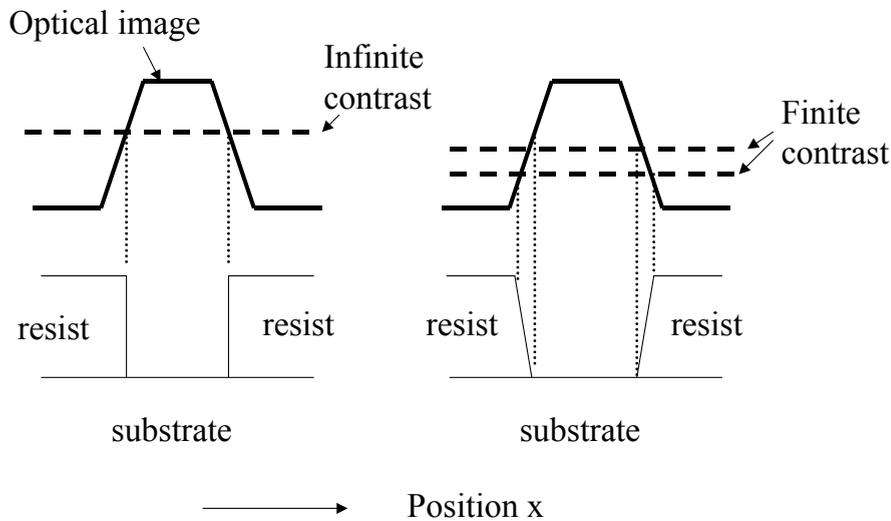
Problem 5 Qualitative Questions (20 points total)

(a) (5 points) Explain why minimum resolution and depth of focus requirements **cannot** be optimized simultaneously by using shorter wavelength photons for projection optical lithography.

We need **small** minimum resolution but **large** depth of focus for IC processing. Large DOF is due to nonplanar surface topography of device structures. Since both min resolution and DOF is proportional to wavelength λ , making λ smaller will not satisfy both requirements simultaneously.

(b) (5 points) Why a high contrast photoresist is advantageous for photolithography?

For identical aerial images with finite slopes, the resist cross section will have steeper slopes when resist contrast is high.

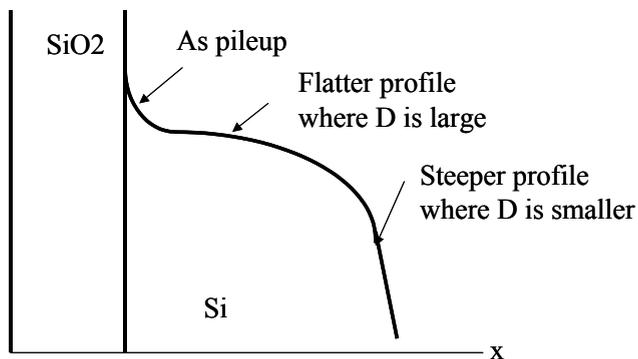


Problem 5 continued

(c) (7 points) A Si wafer has a **high concentration** Arsenic drive-in depth profile. It is then subjected to a thermal oxidation step.

(i) Sketch qualitatively the Arsenic depth profile in Si after the oxidation step. Comment on the slopes of the profile at different regions.

(ii) List all major physical mechanisms which contribute to the enhanced dopant diffusion.



The following mechanisms will all enhance the arsenic diffusion constant

- (A) Electric-field enhancement – build-in electric field established by the spatial gradient of mobile electrons will increase the diffusion constant of the ionized arsenic donor atoms.
- (B) Charge Points Defects – the available electrons from the arsenic donors can create additional charged vacancies and interstitials.
- (C) Oxidation enhanced diffusion – oxidation process can inject extra vacancies/interstitials at the SiO_2 -Si interface.

(iii) (3 points) Why is Transient Enhanced Diffusion “transient”?

Implantation generates excess interstitials and vacancies ($\sim 1000X$ higher than thermal equilibrium) due to nuclear stopping mechanism. The excess point defects will enhance the dopant diffusion. After annealed for a duration of seconds, these excess point defects will recombine. The enhanced dopant diffusion will stop.

Information which may be useful

$1 \mu\text{m} = 10^{-4} \text{cm} = 1000\text{nm} = 10^4 \text{\AA}$

Electron charge $q = 1.6 \times 10^{-19}$ coulombs;

Boltzmann constant $k = 8.62 \times 10^{-5}$ eV/K

n_i of Si $= 3.69 \times 10^{16} \times T^{3/2} \exp[-0.605\text{eV}/kT] \text{cm}^{-3}$

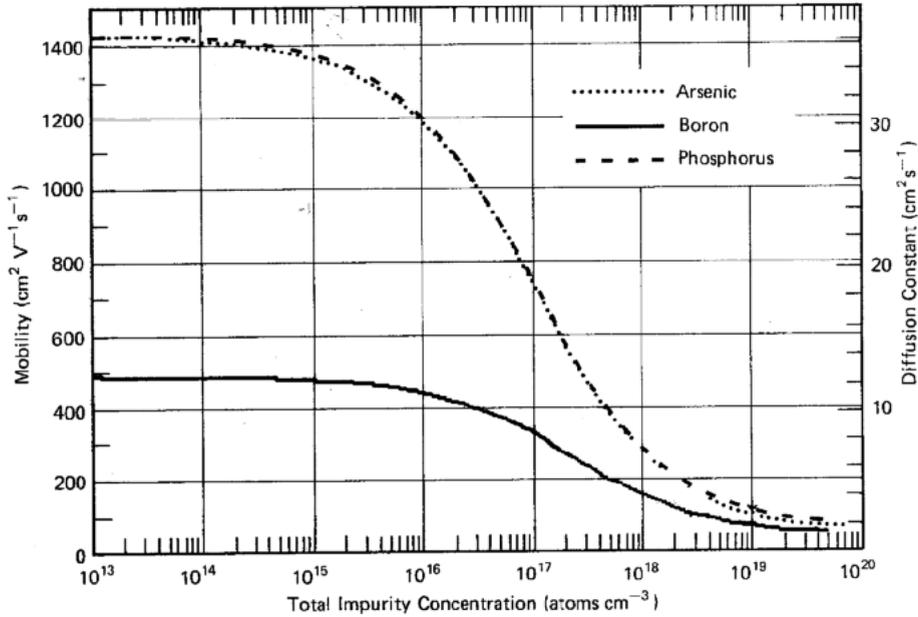
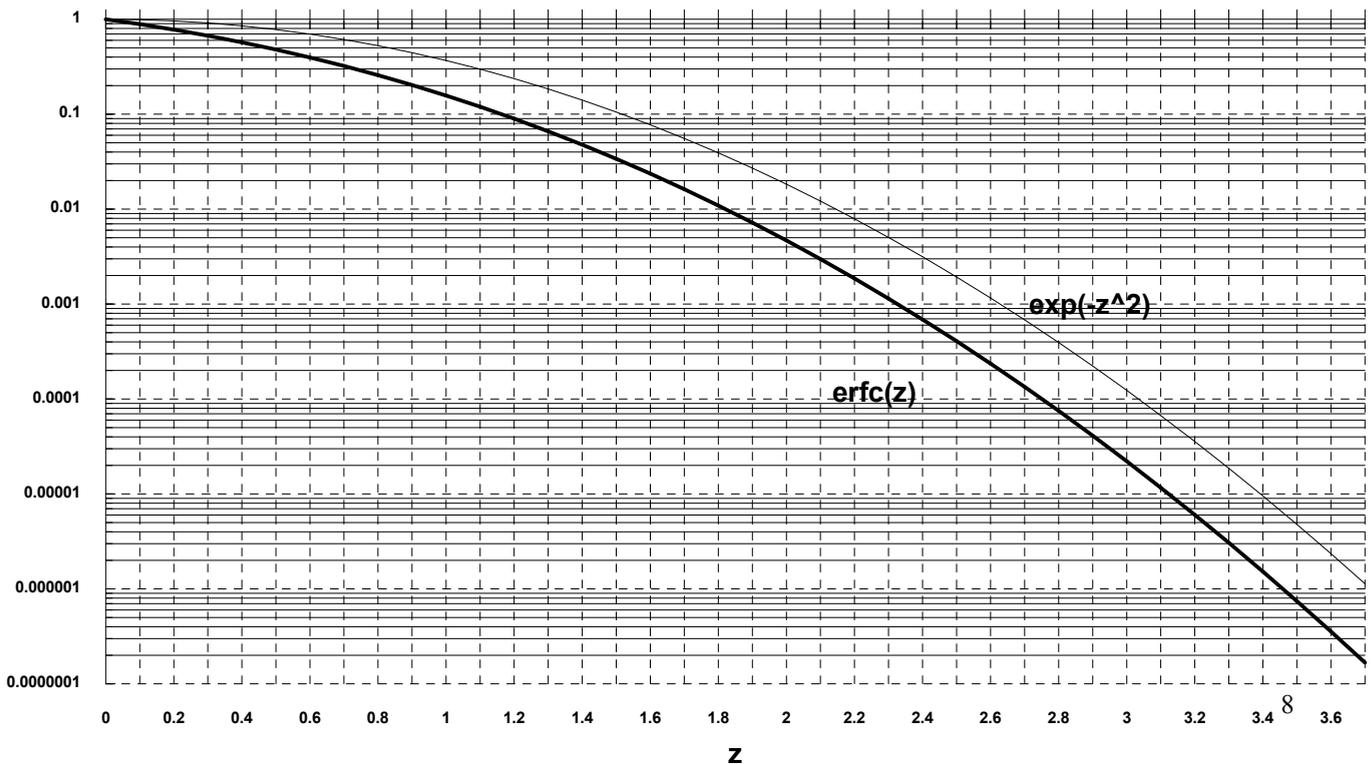
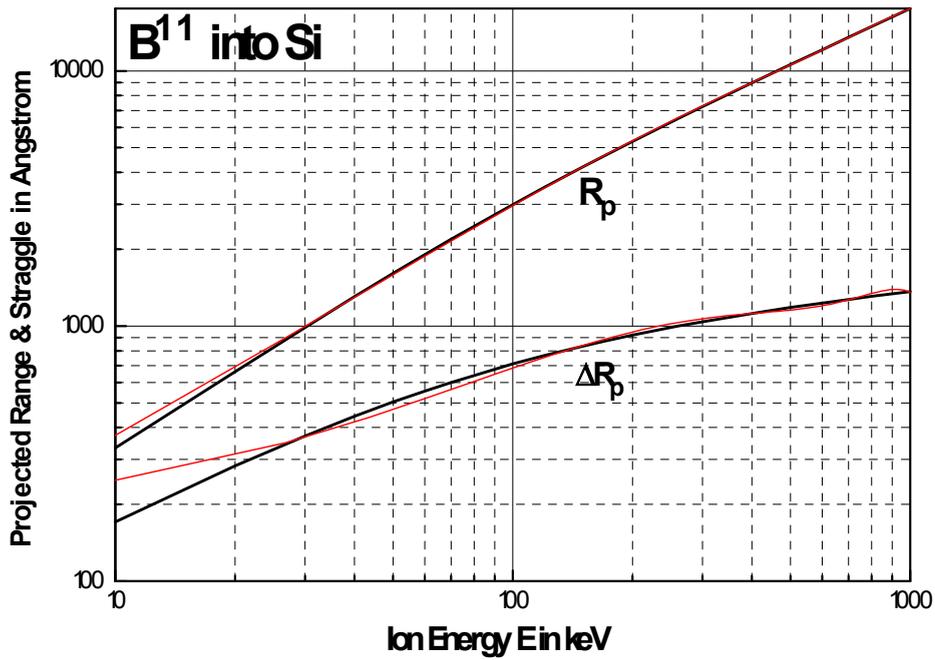


Figure 1.15 Electron and hole mobilities in silicon at 300 K as functions of the total dopant concentration. The values plotted are the results of curve fitting measurements from several sources. The mobility curves can be generated using Equation 1.2.10 with the following parameter values:³



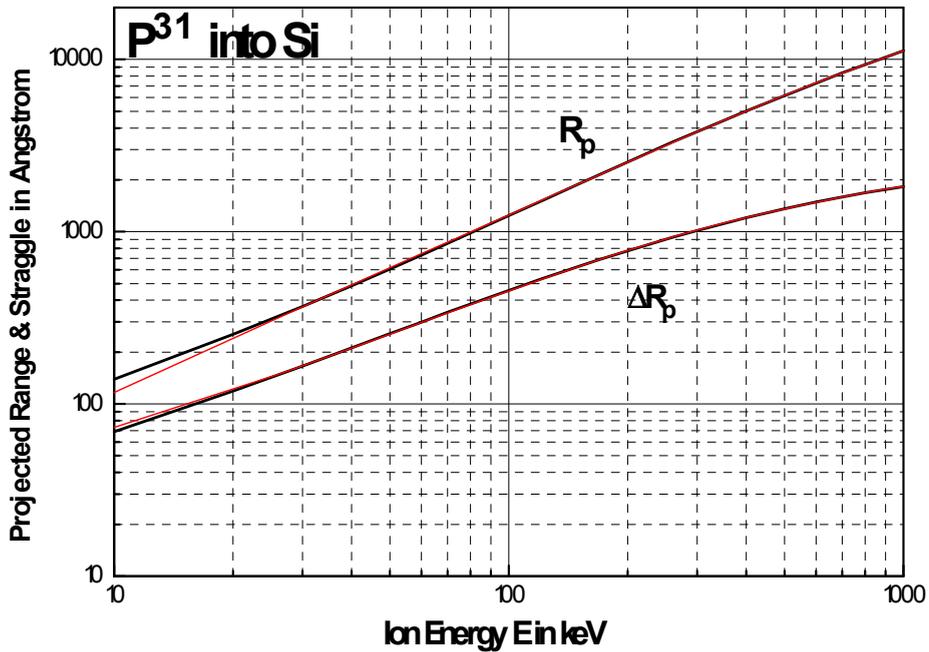
$$R_p = 51.051 + 32.60883 E - 0.03837 E^2 + 3.758e-5 E^3 - 1.433e-8 E^4$$

$$\Delta R_p = 185.34201 + 6.5308 E - 0.01745 E^2 + 2.098e-5 E^3 - 8.884e-9 E^4$$



$$R_p = 7.14745 + 12.33417 E + 0.00323 E^2 - 8.086e-6 E^3 + 3.766e-9 E^4$$

$$\Delta R_p = 24.39576 + 4.93641 E - 0.00697 E^2 + 5.858e-6 E^3 - 2.024e-9 E^4$$



Irvin Curves

