An Introduction to Spreading Resistance Analysis and its Application in the Semiconductor Industry

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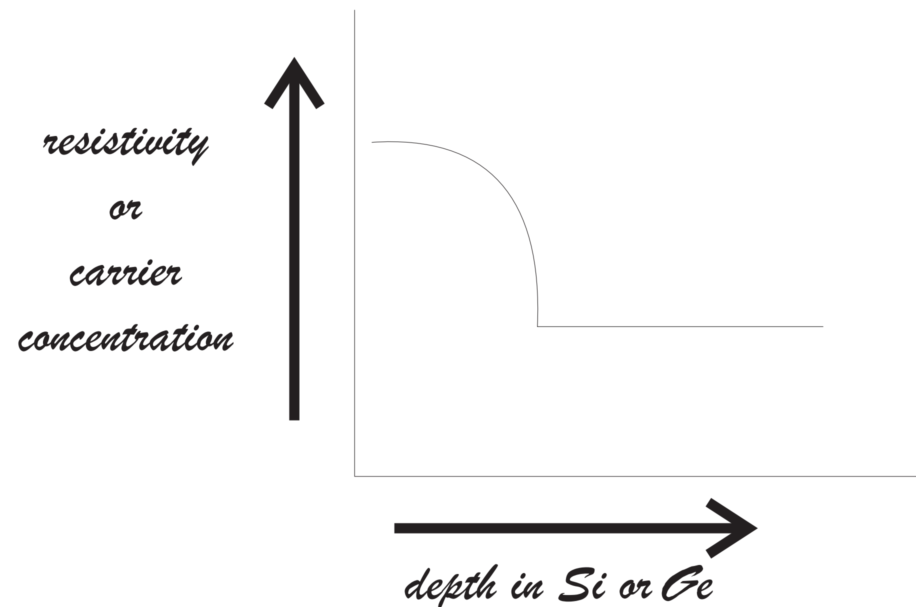
SPREADING RESISTANCE ANALYSIS (SRA) DETERMINES RESISTIVITY-DEPTH IN SILICON AND GERMANIUM



We plan to discuss SRA — using "real-world" profiles whenever possible.

Filling out our request form:

1. Before a job is released to a customer, it is sent to quality control and checked by a senior member of the technical staff. We start the check by reconciling the job with the analysis request form.

2. Filling out our request form with as much detail as possible is extremely helpful. So please do!

3. It helps to determine the optimum bevel angles.

4. Solecon strives for a minimum of 20 data points per layer.

5. For example, a shallow emitter at 0.2µm on a base at 0.4µm on epi/buried layer at 5.5µm on a p-type substrate. What are you really interested in?

6. Solecon Labs' Privacy Policy

How much of the sample do we need?

1. We measure from full wafers down to a millimeter square.
2. Pattern wafers and backups.

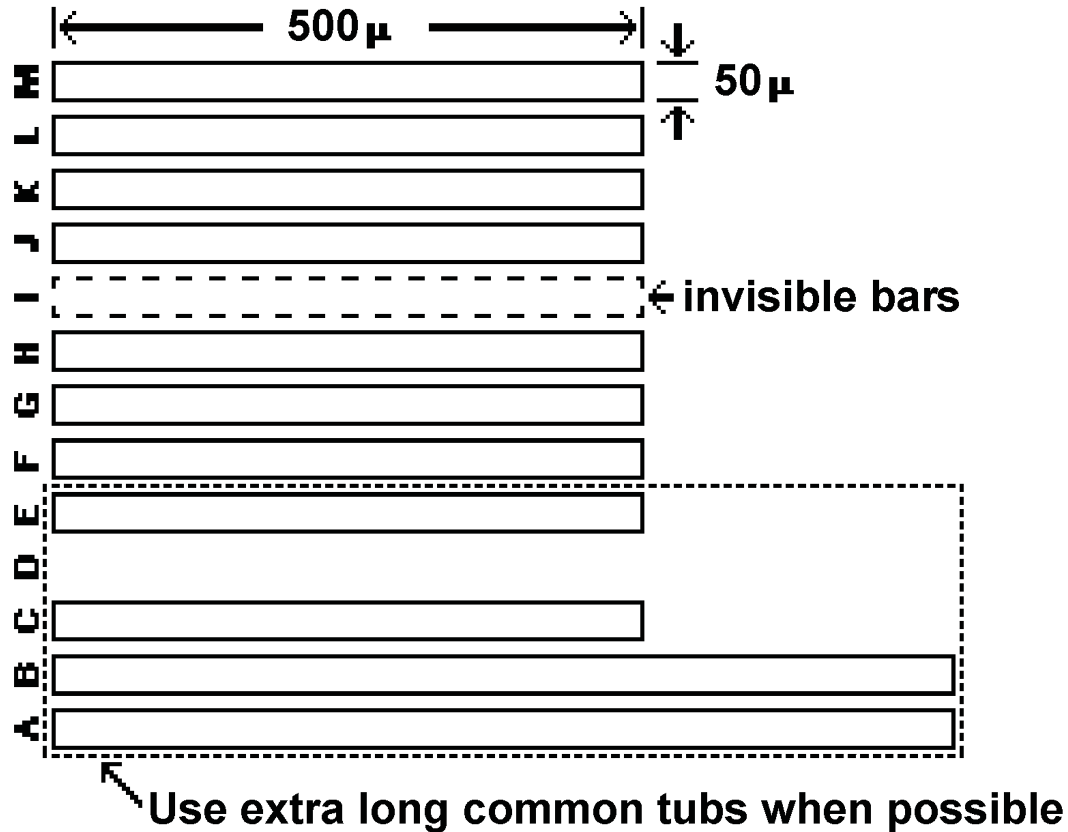
Beveling:

1. Your samples are mounted via their backsides onto predetermined angle beveling blocks.
2. The blocks are attached to a beveling jig.
3. Then placed (upside down!) on conditioned glass, dressed with fine grit polycrystalline diamond slurry.
4. Samples should be beveled immediately before probing, to avoid interference from native oxide.

Size of pattern:

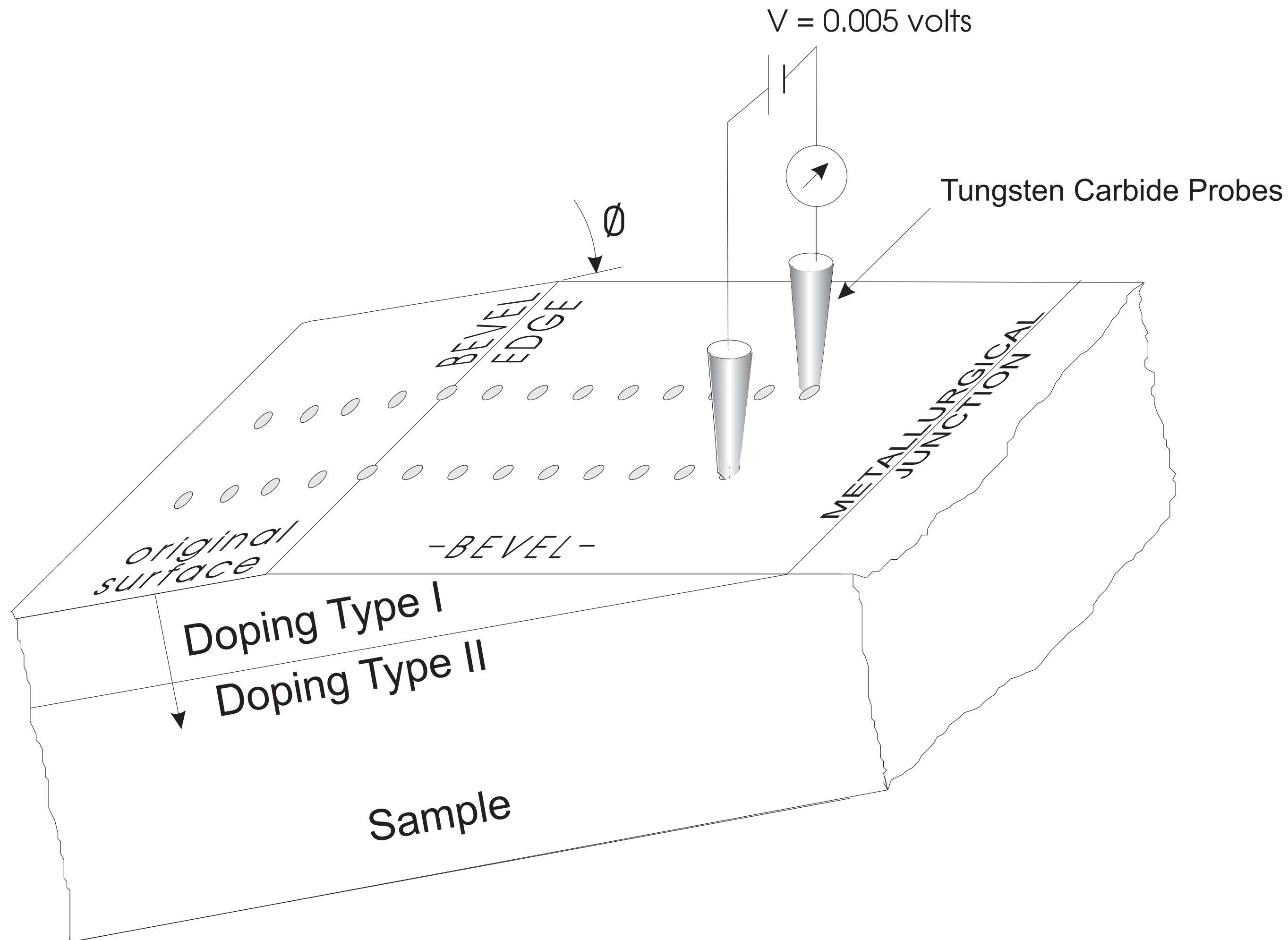
1. Our minimum requirements are 20µm wide x 100µm long.
2. The smaller the pattern size the greater the compromise.
3. For this reason we suggest dedicated spreading resistance test patterns which are 50 x 500µm or larger.

Dedicated SRA Test Patterns

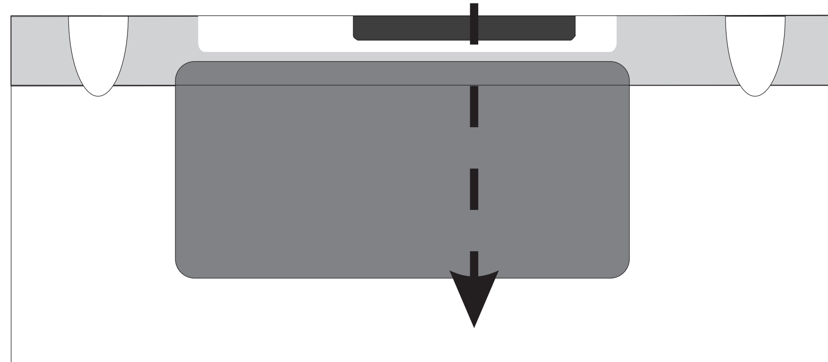


Recommended for Scribeline use Only

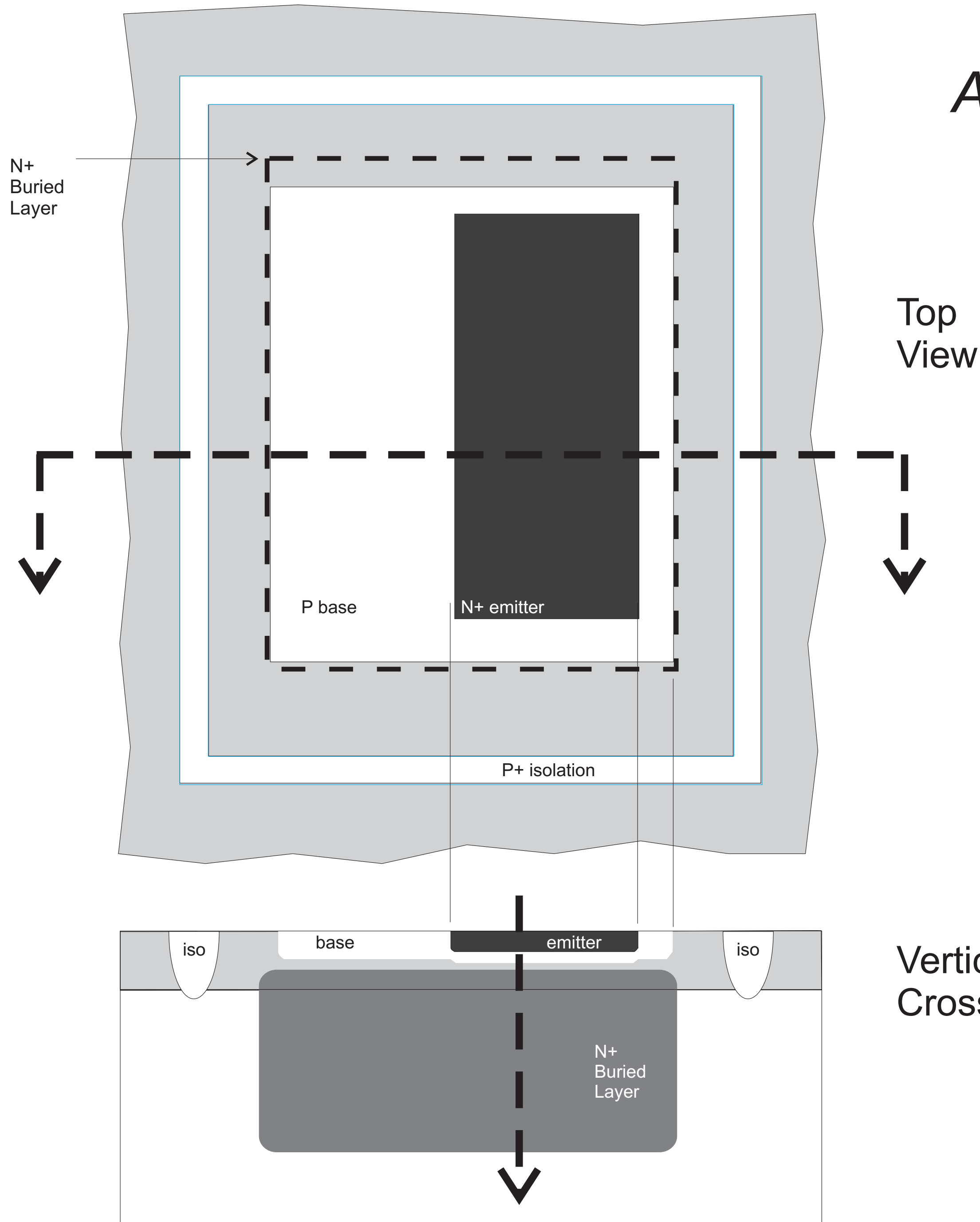
Schematic diagram of a spreading resistance measurement on a beveled sample



A BIPOLAR PROFILE



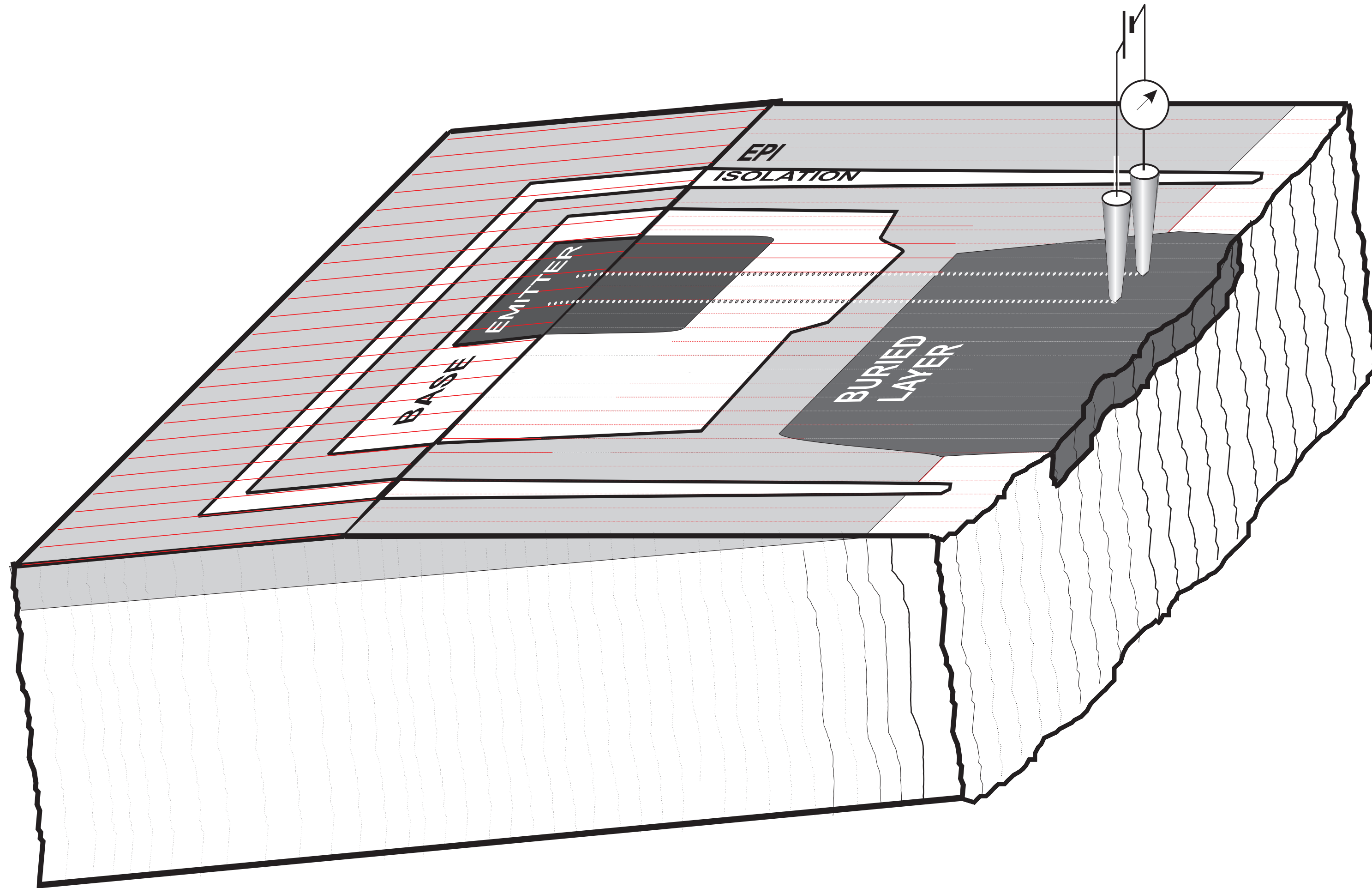
A Bipolar Structure To Be Profiled



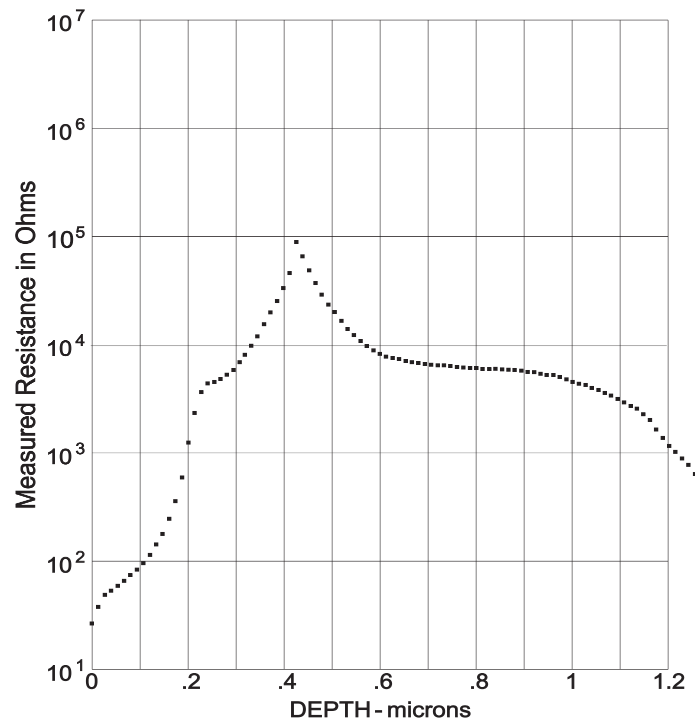
Top
View

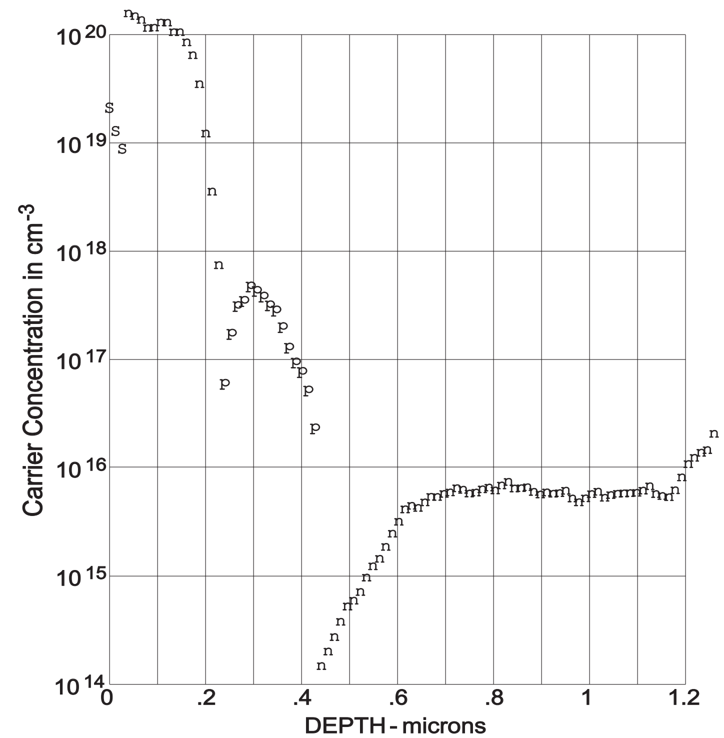
Verticle
Cross Section

Shallow Profile of the Bipolar Structure

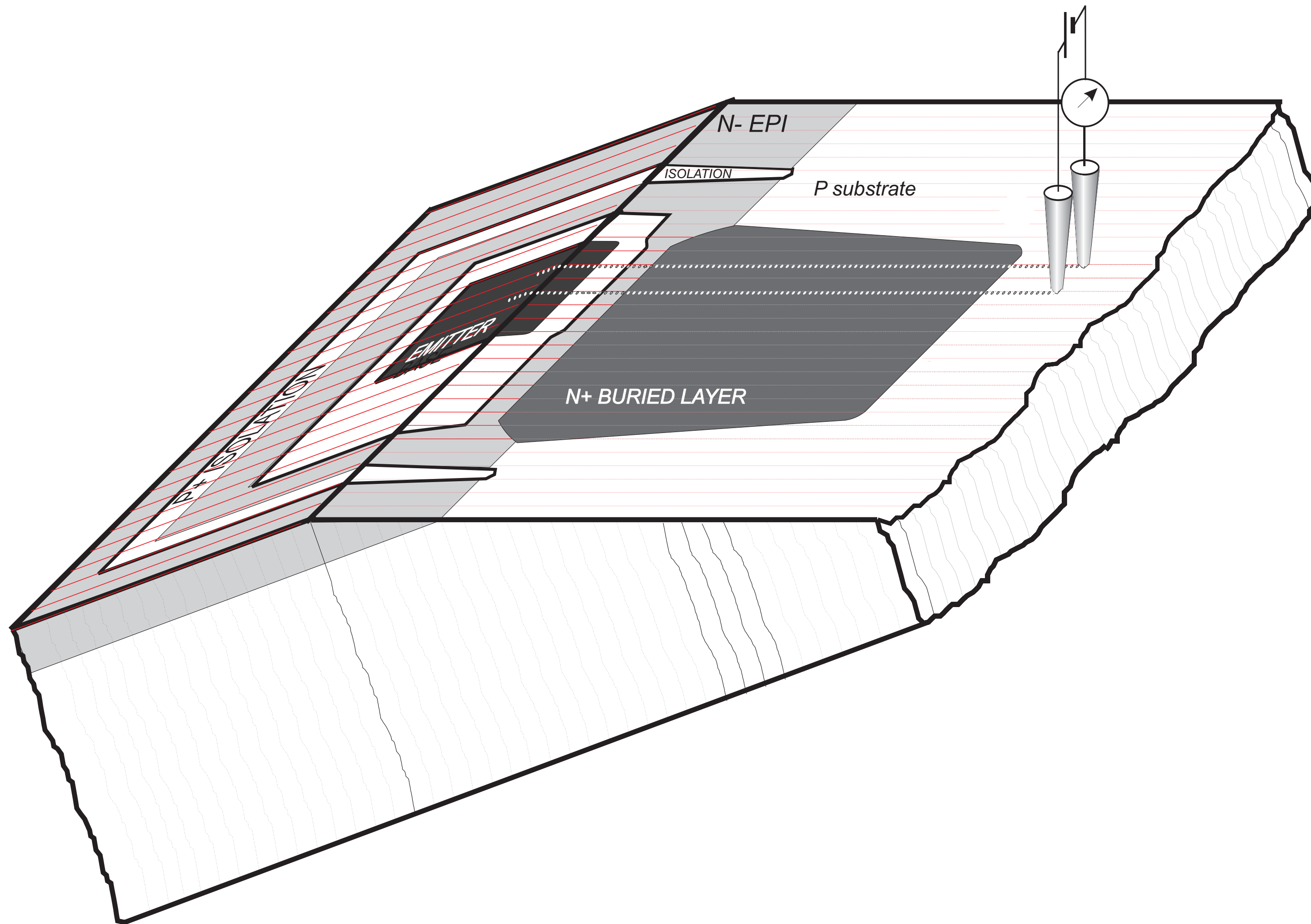


Bipolar Transistor (shallow profile)

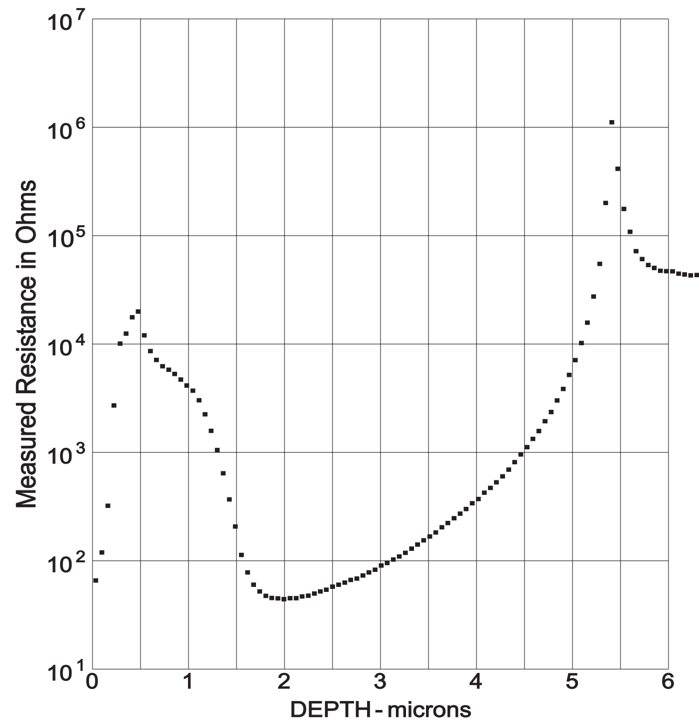


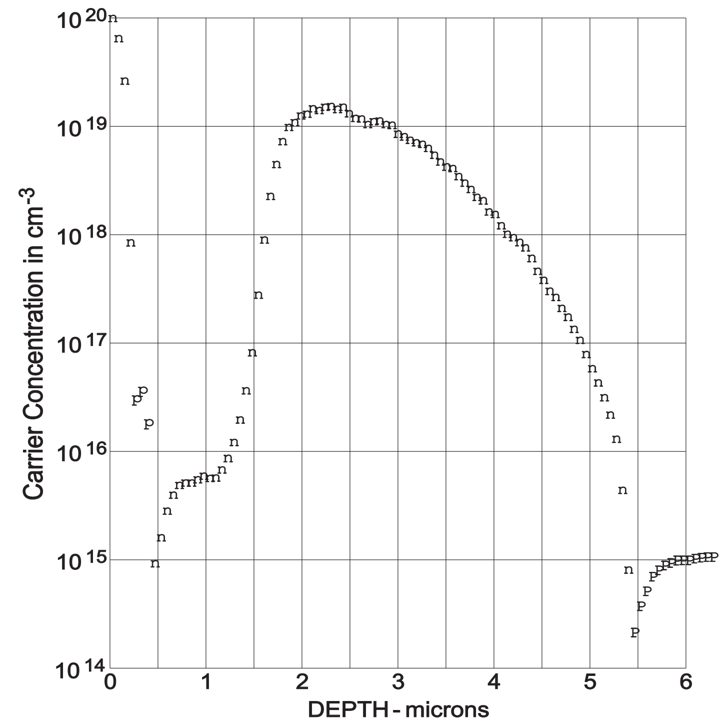


Deep Profile of the Bipolar Structure

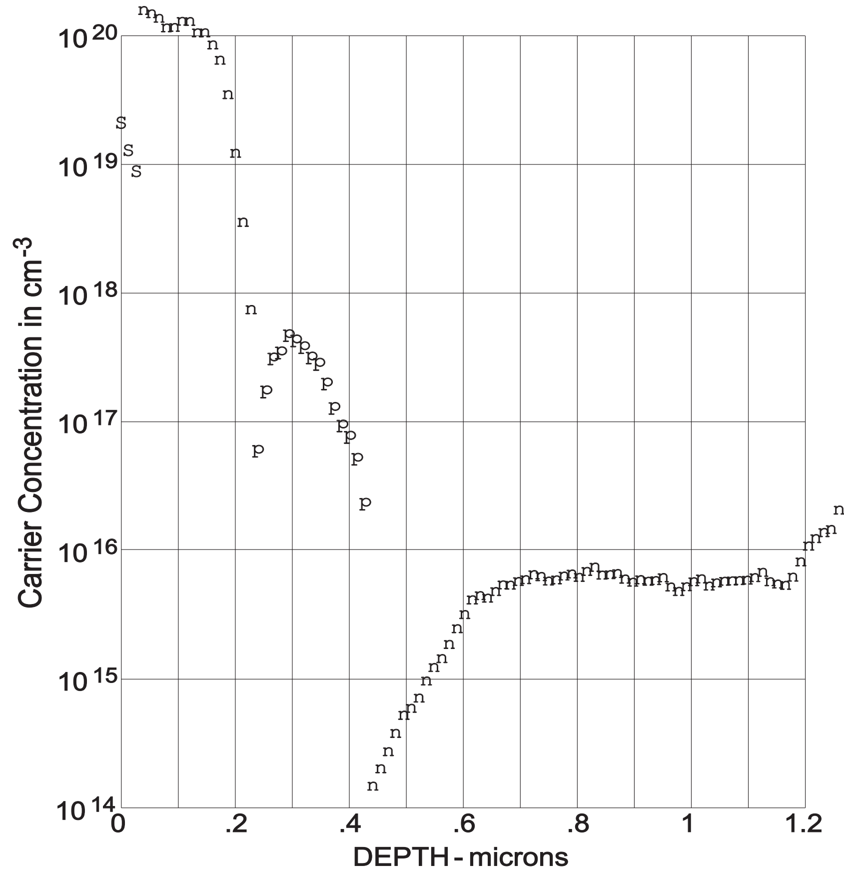


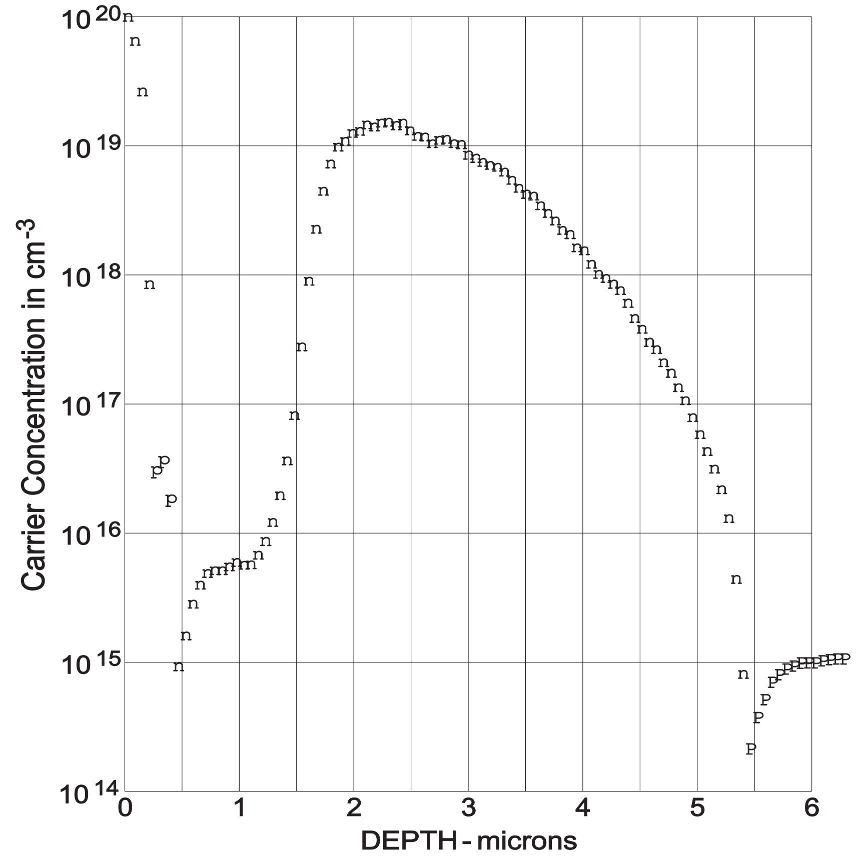
Bipolar Transistor (deep profile)





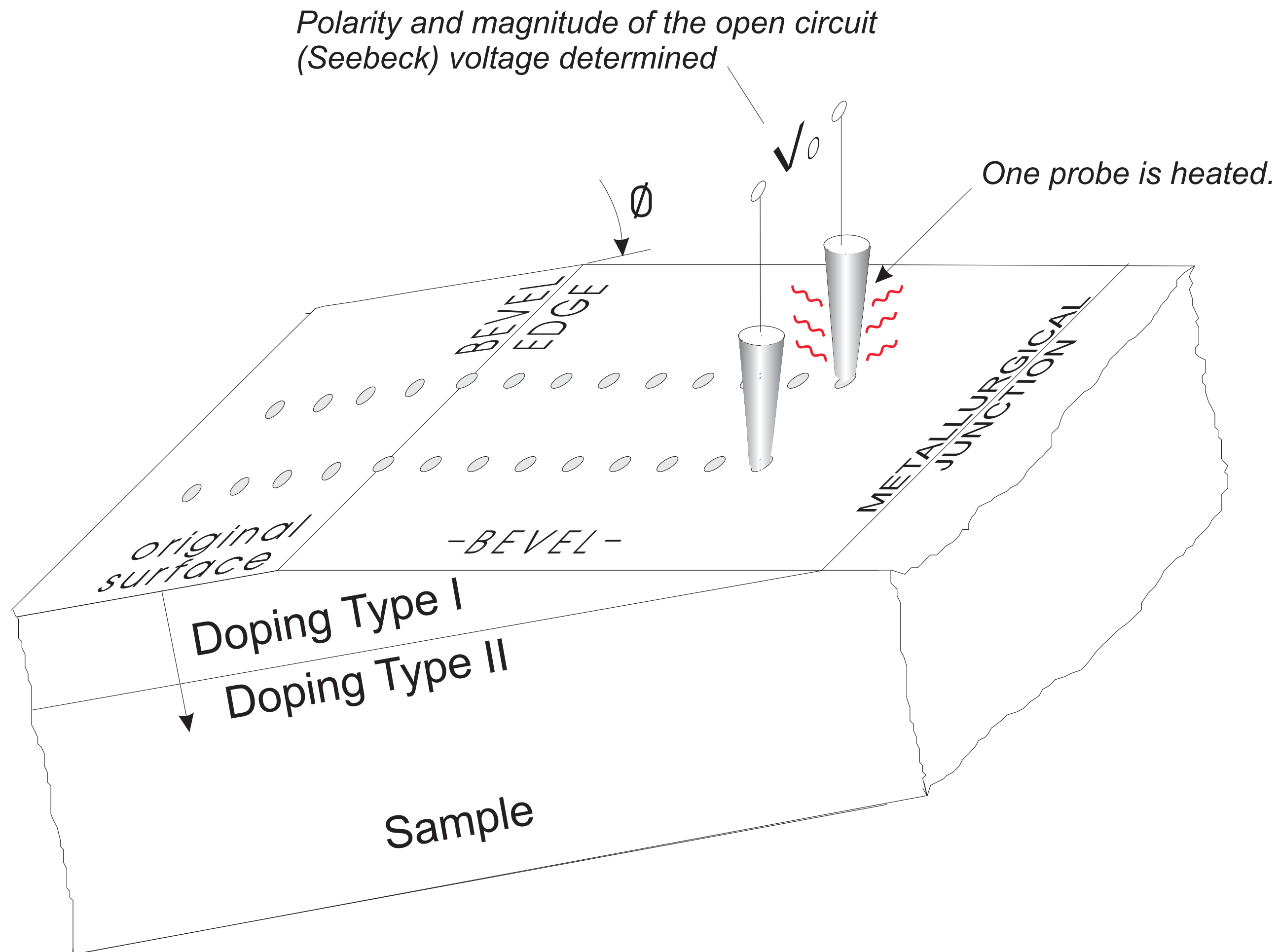
Bipolar Transistor



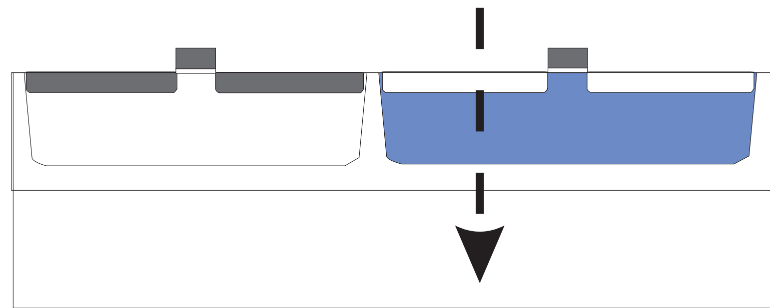


Carrier Type Determination

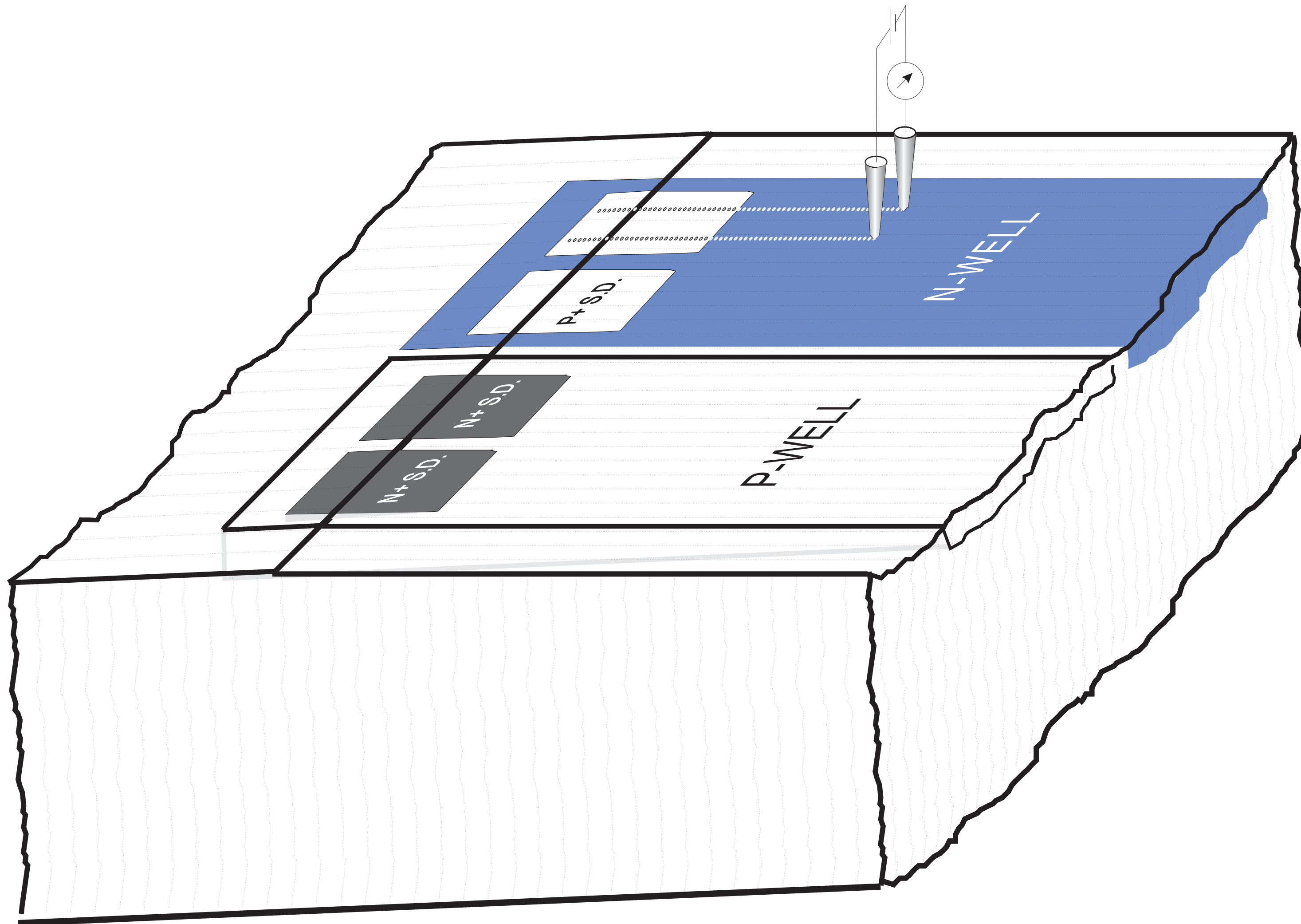
With a Few Modifications, the Spreading Resistance Set-Up Can Determine "N" or "P".



A CMOS PROFILE

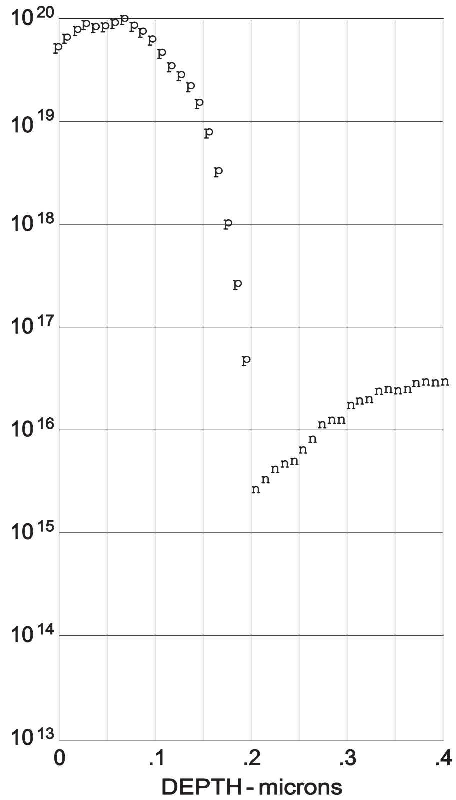


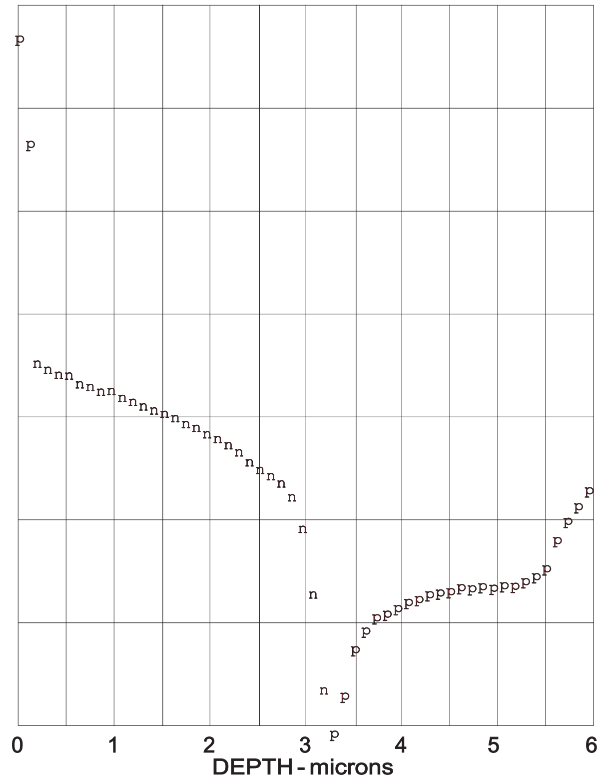
SHALLOW PROFILE OF THE CMOS STRUCTURE

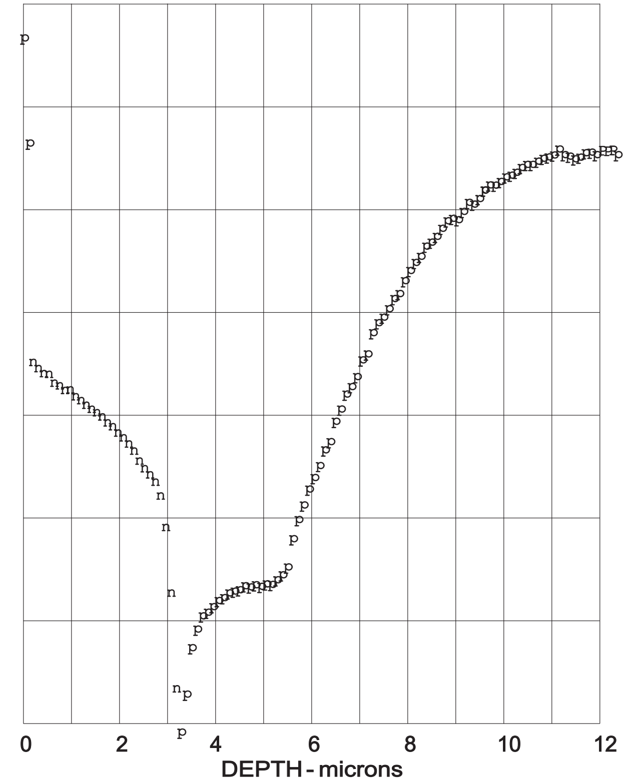


DEEP PROFILE OF THE CMOS STRUCTURE

CMOS (P-channel Source-Drain)



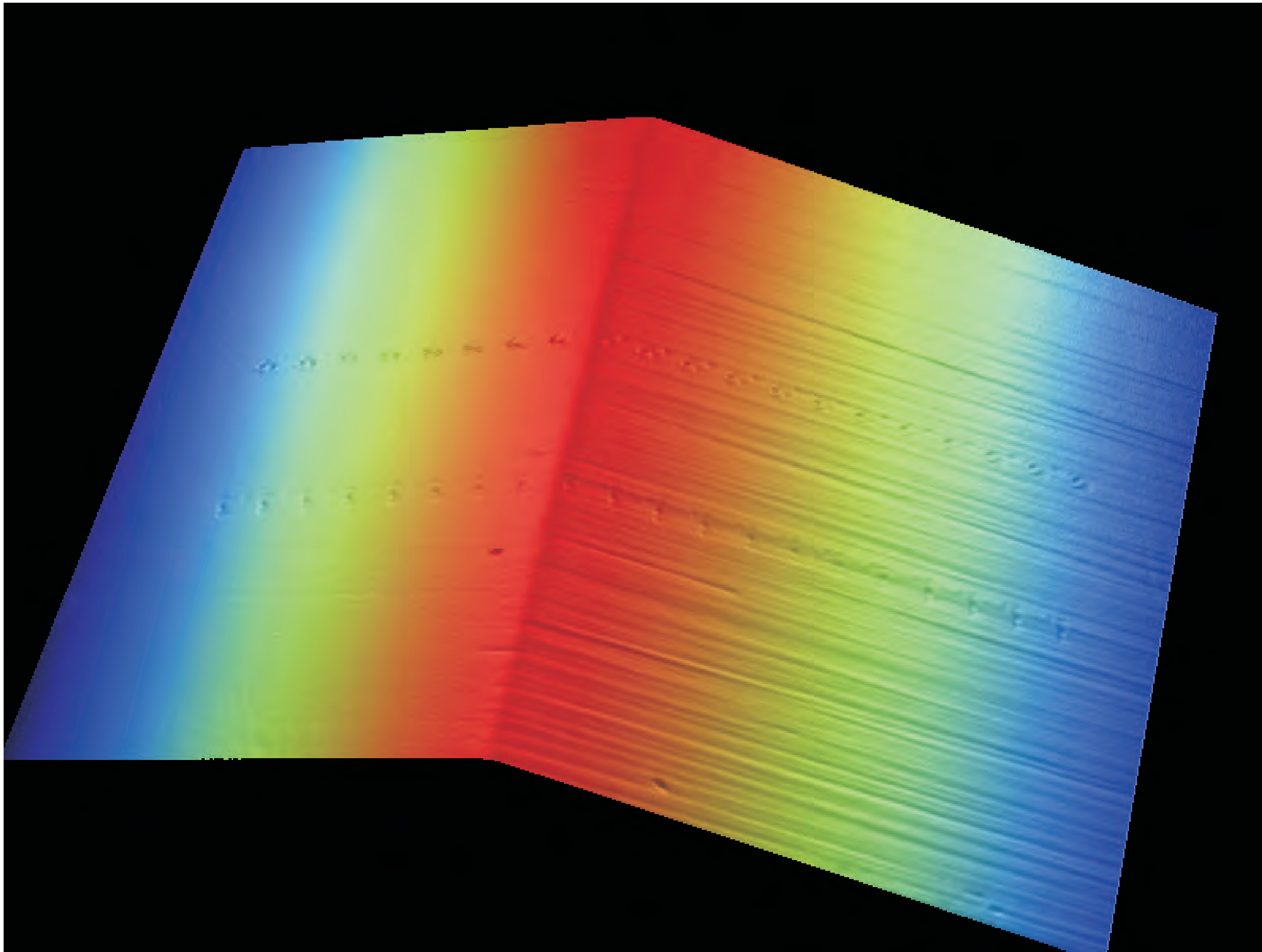




Shallow Profile to
Characterize the Source-Drain

Steeper Profile (Plotted on 2 Depth Scales)
to Characterize the
N-Well, Epi, and Substrate

Optical Profilometer view of a spreading resistance measurement on a beveled sample



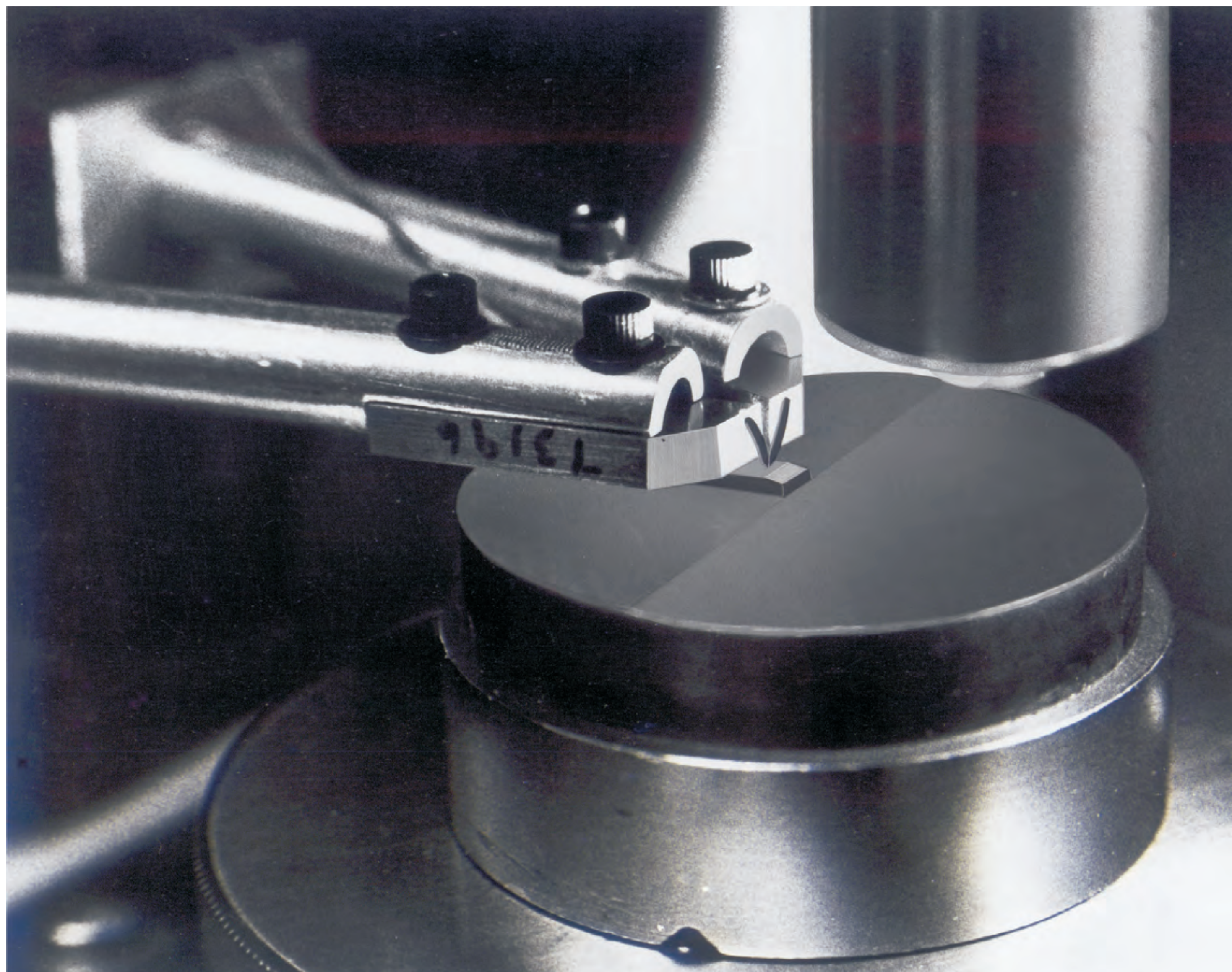
Probing

1. 2 probe tips made of tungsten carbide are used.
2. The probe tips are shaped so that they can be positioned within 20um of each other.
3. Each probe tip is mounted on the end of a separate arm.
4. Each arm pivots on a kinematic bearing system that eliminates lateral motion or "scrubbing" as it contacts the sample.
5. Probe tips are lowered gently onto the sample.
6. Because of the small contact area, pressure is in excess of a million pounds per square inch.
7. 5 millivolts are applied across the probes and the resistance is measured.

Probing (continued)

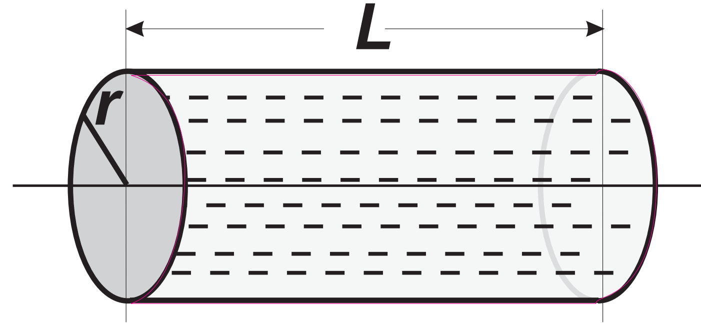
8. Solecon Labs uses an extensive calibration set of 64 NIST traceable samples divided into <111> and <100> for both P and N type.
9. Each group has 16 samples ranging from 0.001 ohm-cm to 200 ohm-cm.
10. Care must be taken to see that probes travel in a path free of scratches.
11. Probes must travel perpendicular to the bevel edge.
12. Step increments are large enough to prevent overlap.
13. Preparation of probe tips is an art.
14. Minimum penetration, close spacing of probes and minimal damage to sample are requirements for good probe tips.

Bird's Eye View of SRA Sample and Probes



LINEAR CURRENT FLOW

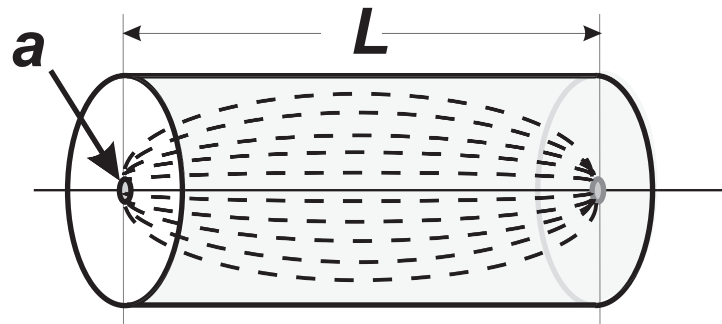
$$R = \frac{\rho L}{\pi r^2}$$



where ρ is the bulk resistivity in ohm-cm

SPREADING RESISTANCE

$$R = \frac{\rho}{2a}$$



where a is the radius of the contact area

What is the significance of resistivity? In a semiconductor it is related to the concentration of electrons and holes:

$$\sigma = \frac{1}{\rho} = nq\mu_e + pq\mu_p$$

- σ: Conductivity in $ohm^{-1}cm^{-1}$ or mho cm^{-1}
- ρ: Resistivity in ohm-cm
- n: Electrons/cm^3
- q: Charge on an electron (1.60218E-19 Coulombs)
- μ_e: Electron Mobility (cm^2/V-s)
- p: Holes/cm^3
- q: Charge on an electron (1.60218E-19 Coulombs)
- μ_p: Hole Mobility (cm^2/V-s)

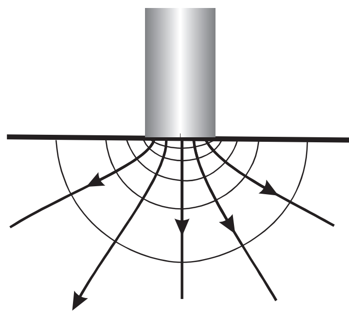
And from that, the dopant concentration can be approximated.

$$N \cong n \cong \frac{1}{\rho q \mu_e}$$

Calibration Chart

Spreading Resistance *vs.* Resistivity

(NIST Traceable Si Bulk Standards)



Measured Resistance (ohms)

10^7

10^6

10^5

10^4

10^3

10^2

10

1

n<111>

n<100>

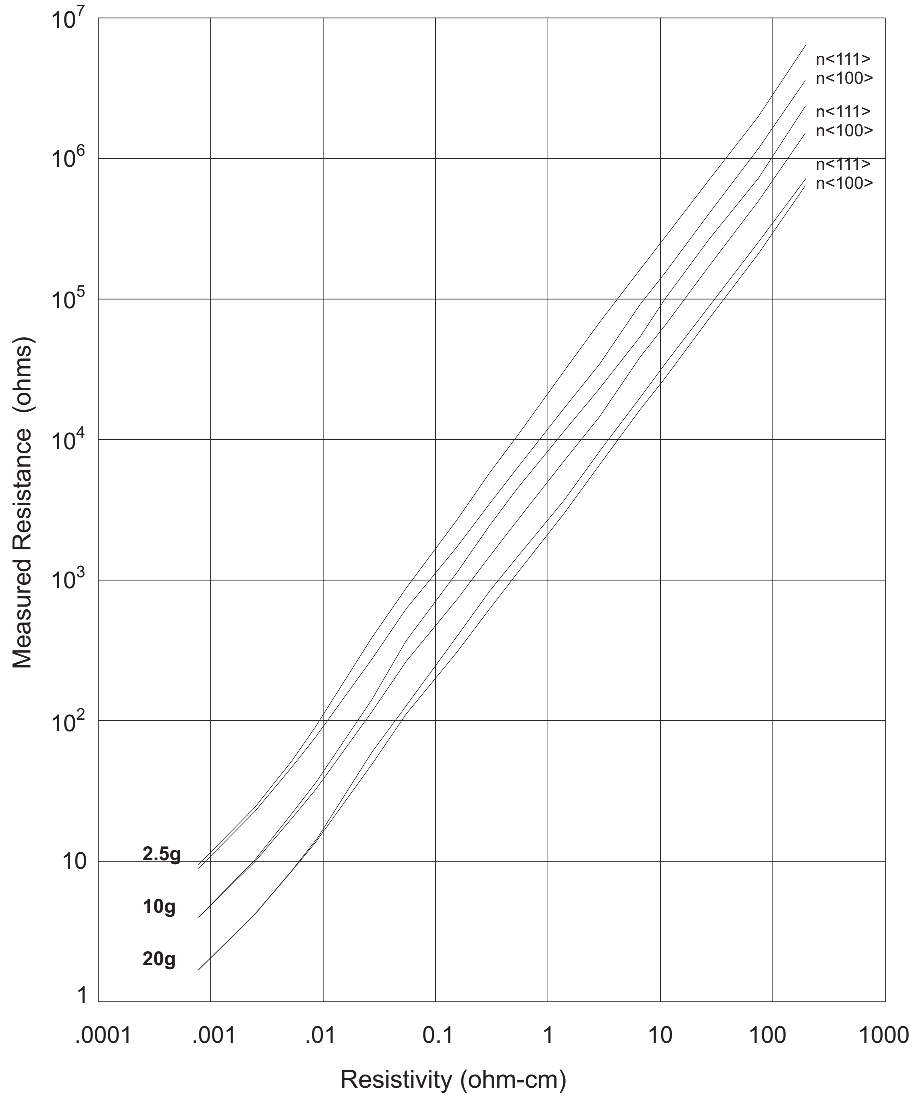
p<111>

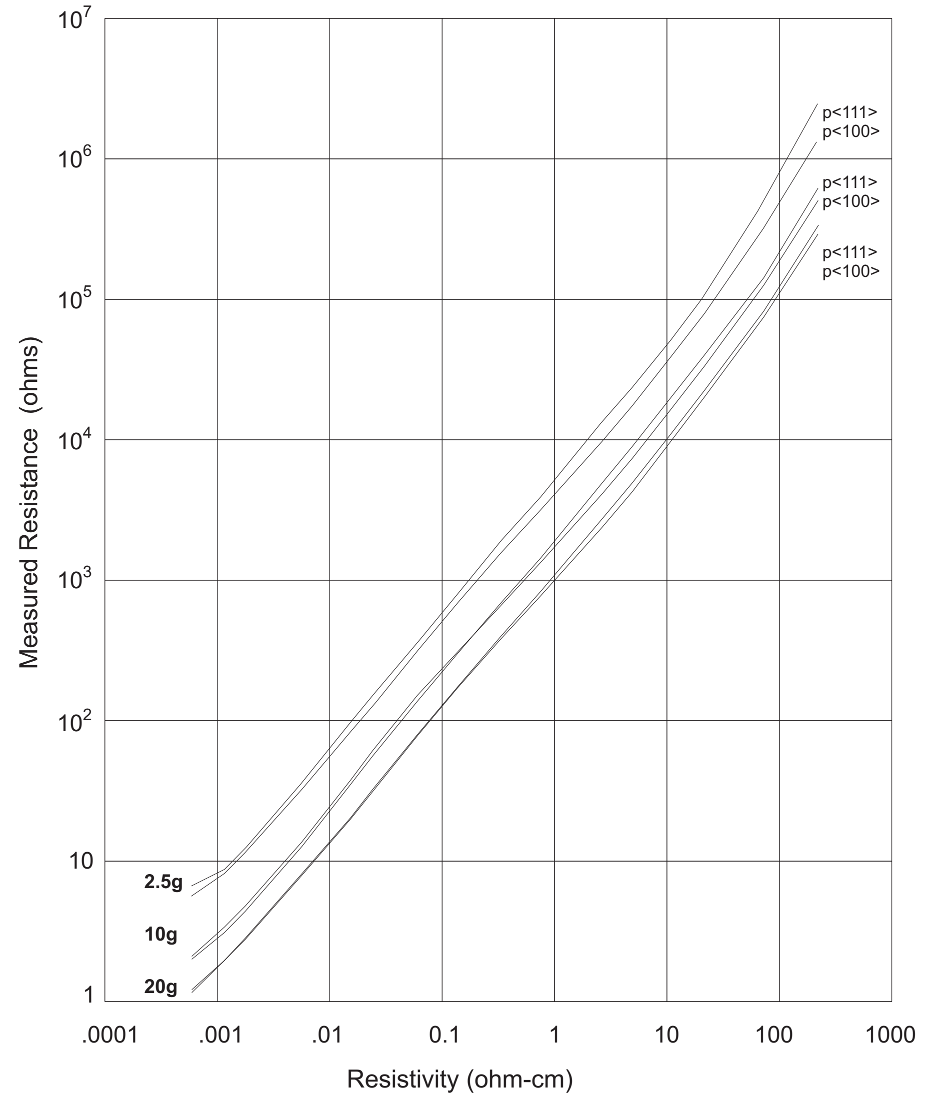
p<100>

.0001 .001 .01 0.1 1 10 100 1000

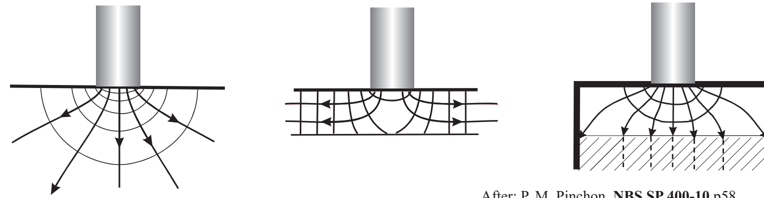
Resistivity (ohm-cm)

Calibration Data for Three Probe Loads





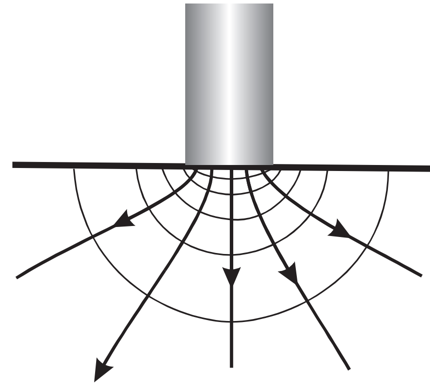
DATA REDUCTION



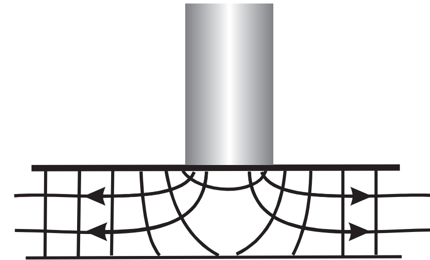
After: P. M. Pinchon, **NBS SP 400-10** p58

Current Lines and Equipotential Surfaces:

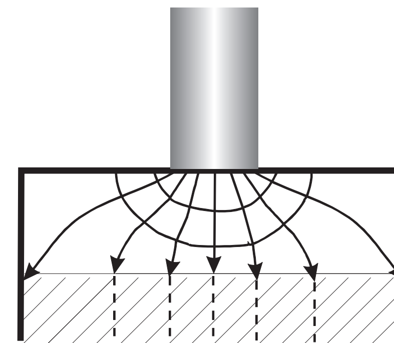
BULK SAMPLES (i.e. starting wafers, most wafer substrates, and SRA calibration standards).



THIN LAYERS (or any structure as it approaches a junction or insulating boundary).

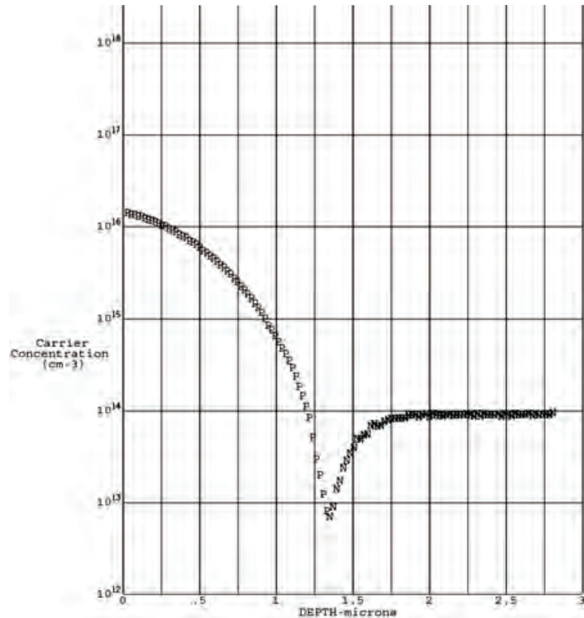


LAYERS WITH LOWER RESISTIVITY UNDERNEATH:
n-epi on N+ buried layer (bipolar)
n-epi on N+ substrate (CMOS)
p-epi on P+ substrate (CMOS)

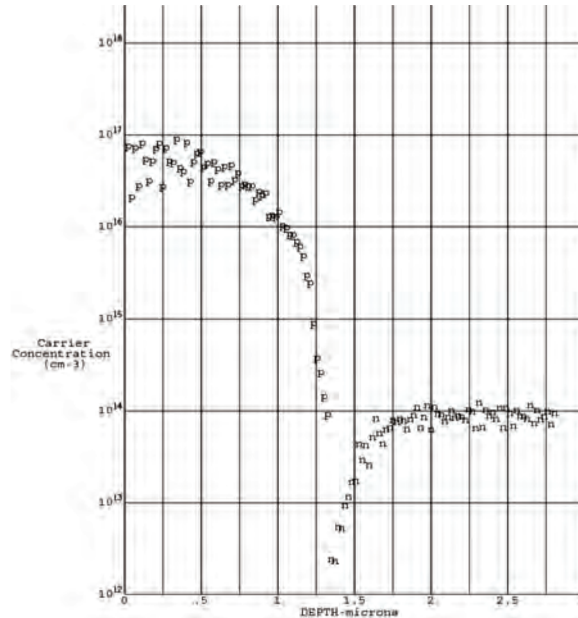


After: P. M. Pinchon, **NBS SP 400-10** p58

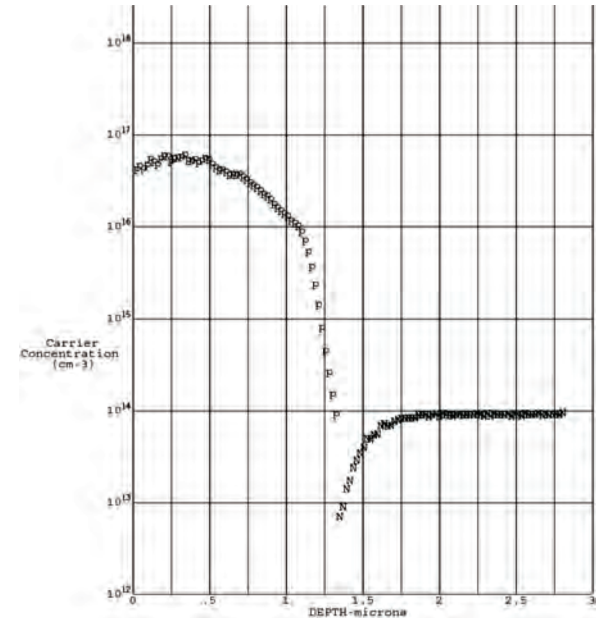
Sampling Volume Correction



Uncorrected layers
(Unsmoothed data)



Both layers corrected
(Unsmoothed data)



Top layer corrected and smoothed
(Uncorrected/unsmoothed substrate)

Our correction algorithms account for the sampling volume on non-uniformly doped layers. In regions with slight to no resistivity gradient, the algorithms tend to magnify the mechanical noise. But without correction the graded layer's values can be very wrong! We have various levels of smoothing which we can use to reduce the scatter in your profiles.

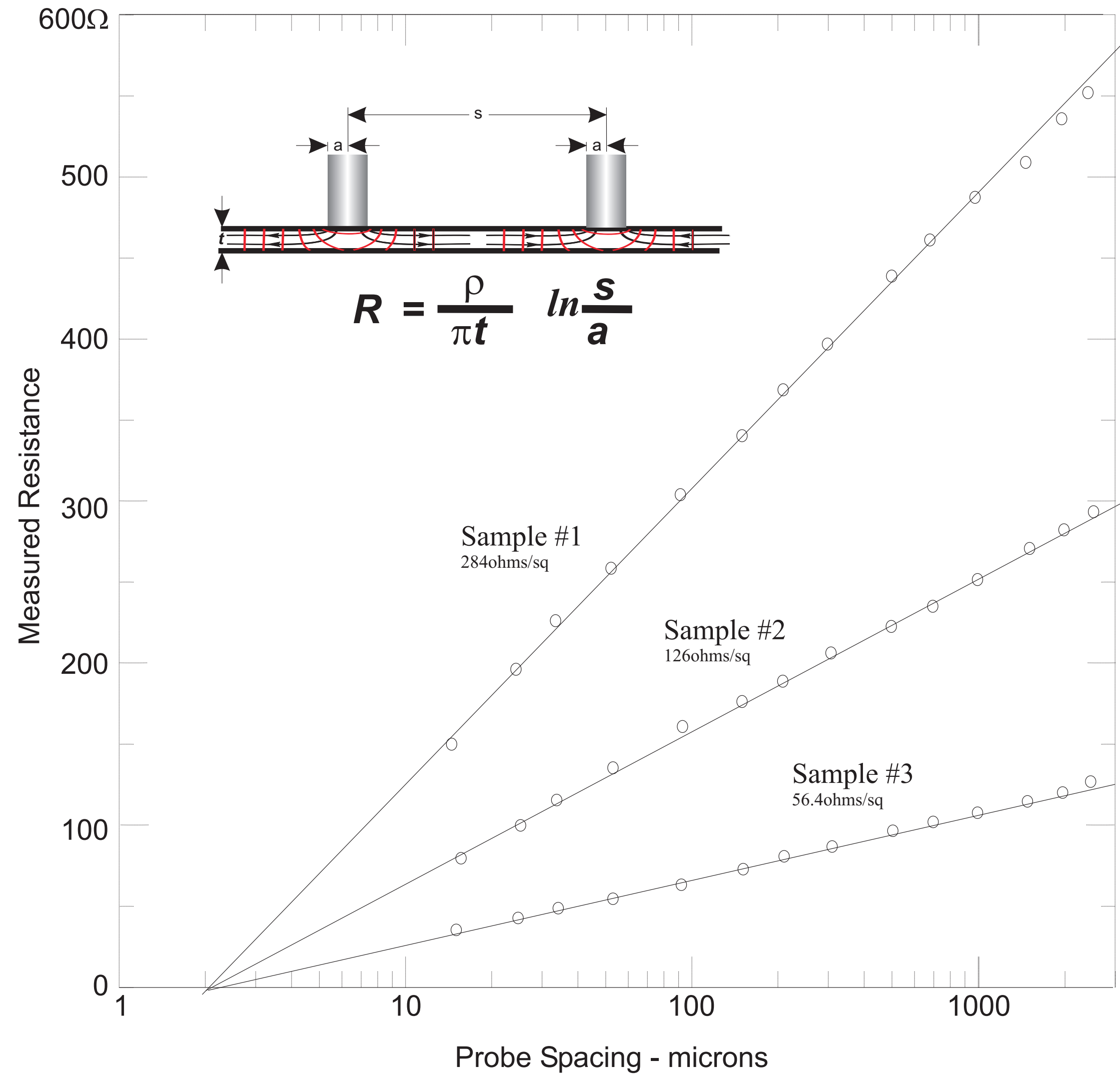
Two Probes on a Thin Layer (t<a):

$$R = \frac{\rho}{\pi t} \ln \frac{s}{a}$$

D. H. Dickey, **NBS SP 400-48**

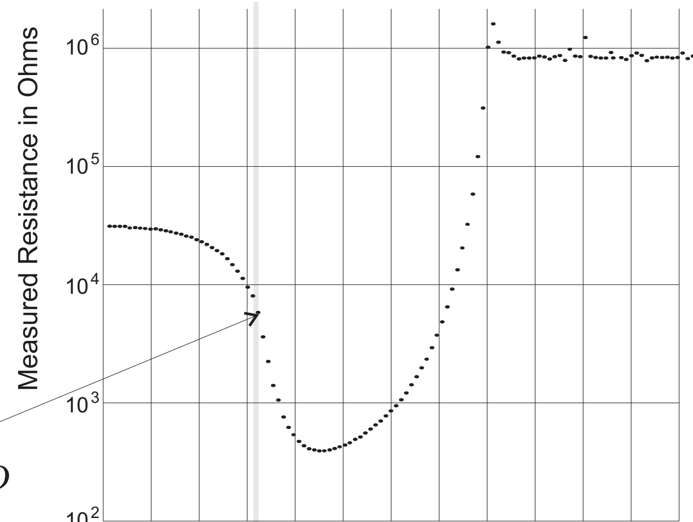
Probe Spacing Experiment on Relatively Thin Layers

(Measured resistance is dominated by the lateral current flow)



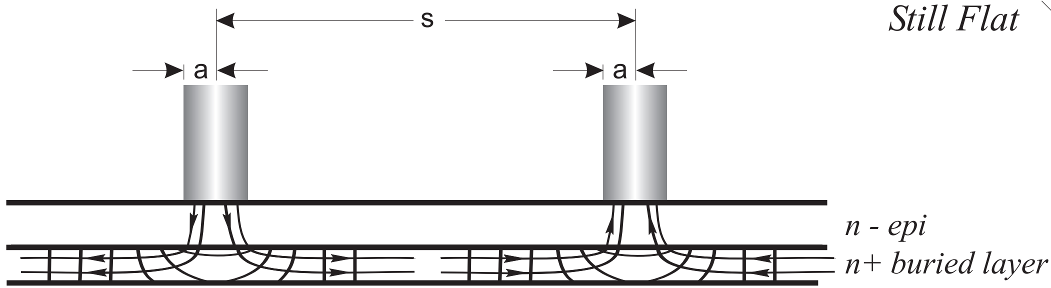
After: Dickey, **NBS SP 400-48 p16**

A DATA REDUCTION CHALLENGE:
Thin Epi / Buried Layer (same type)

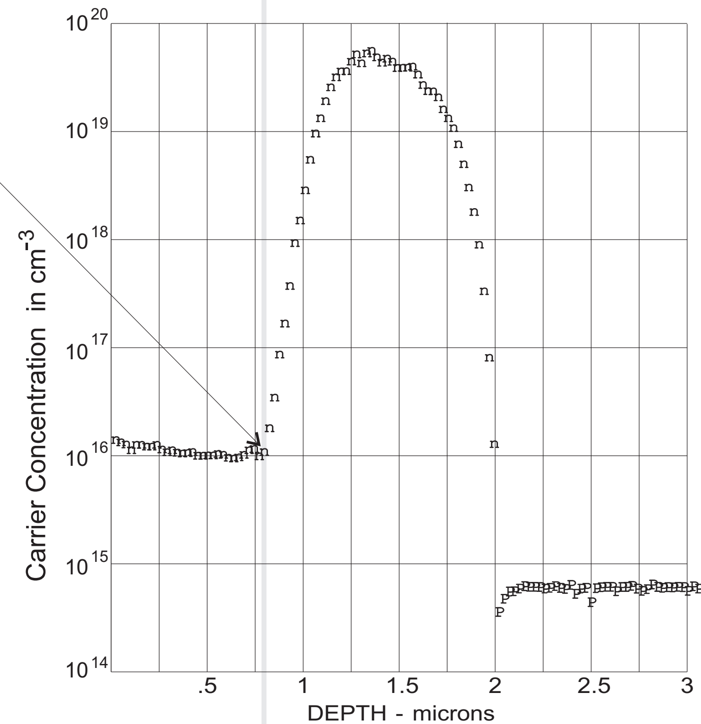


Measured Resistance Has DECREASED 5X!

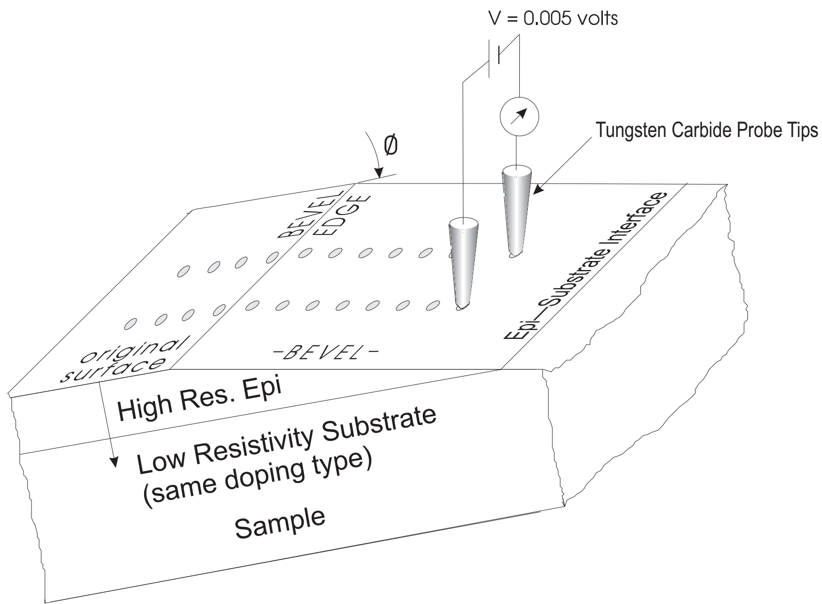
Concentration Still Flat

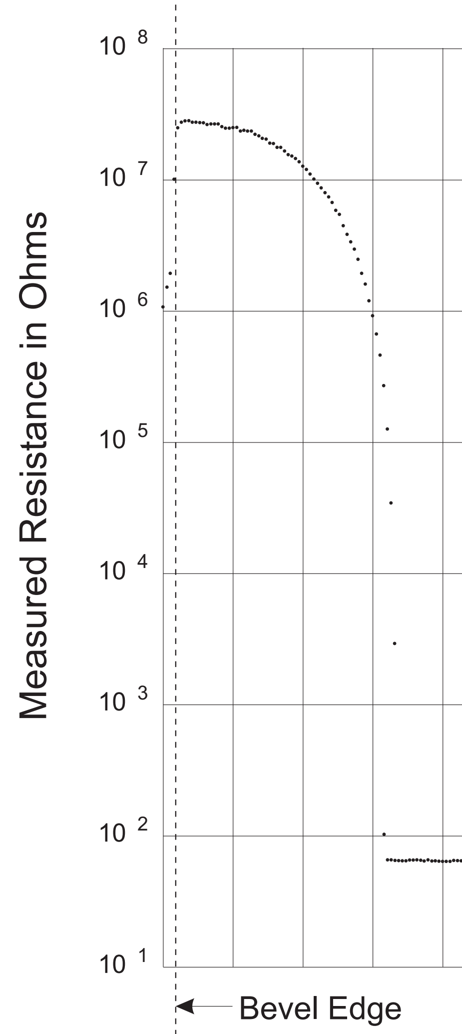


n - epi
n+ buried layer



High Resistivity Epi

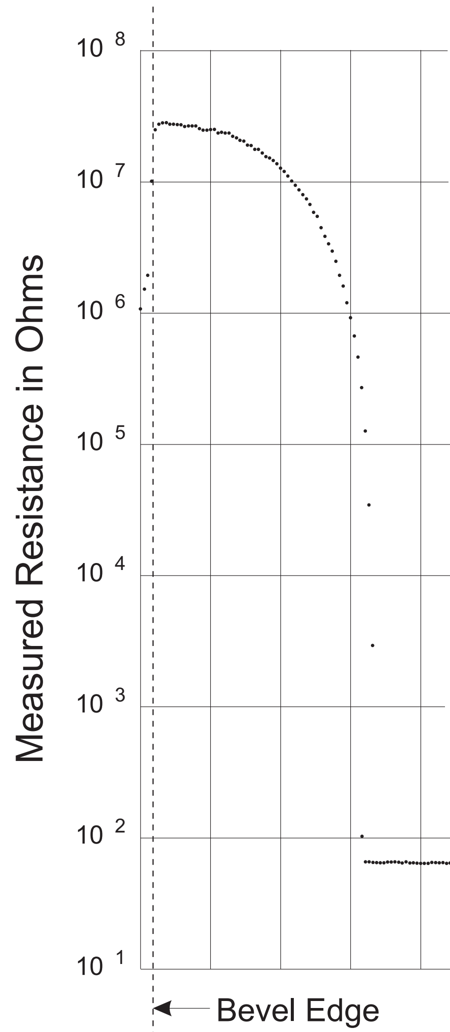




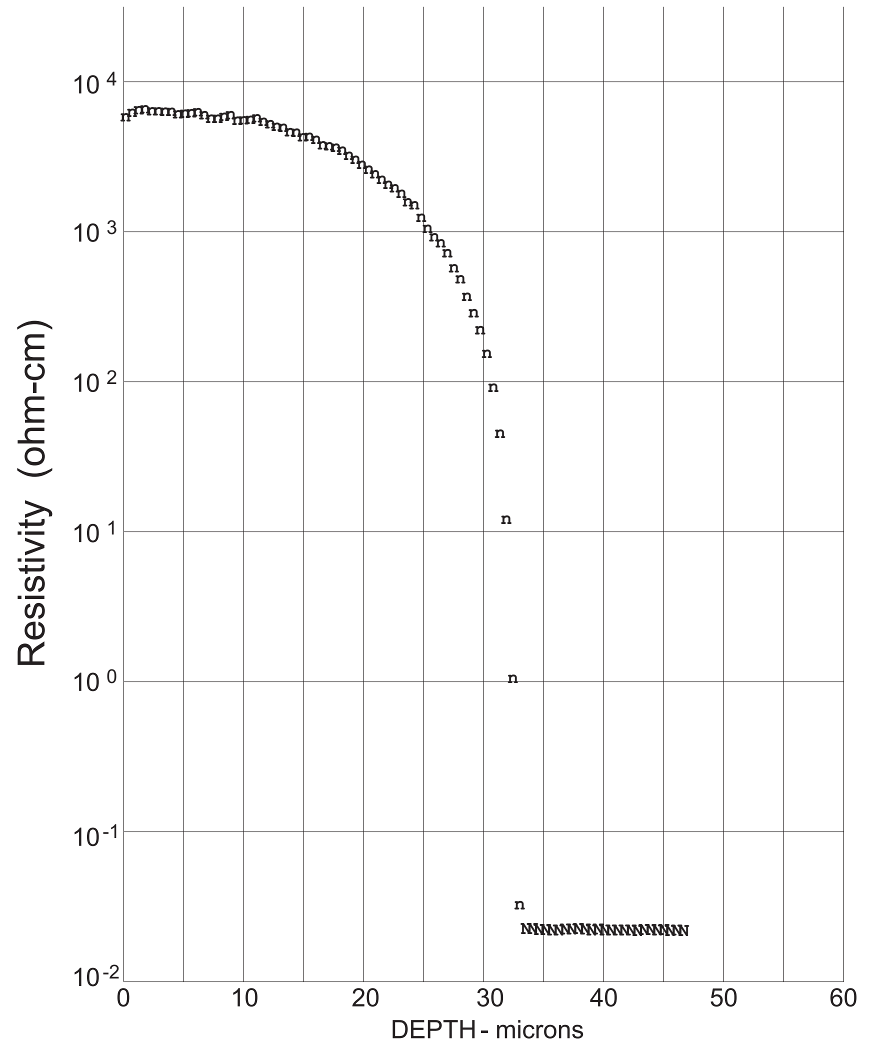
Probing

"Raw Data"

High Resistivity Epi (continued)



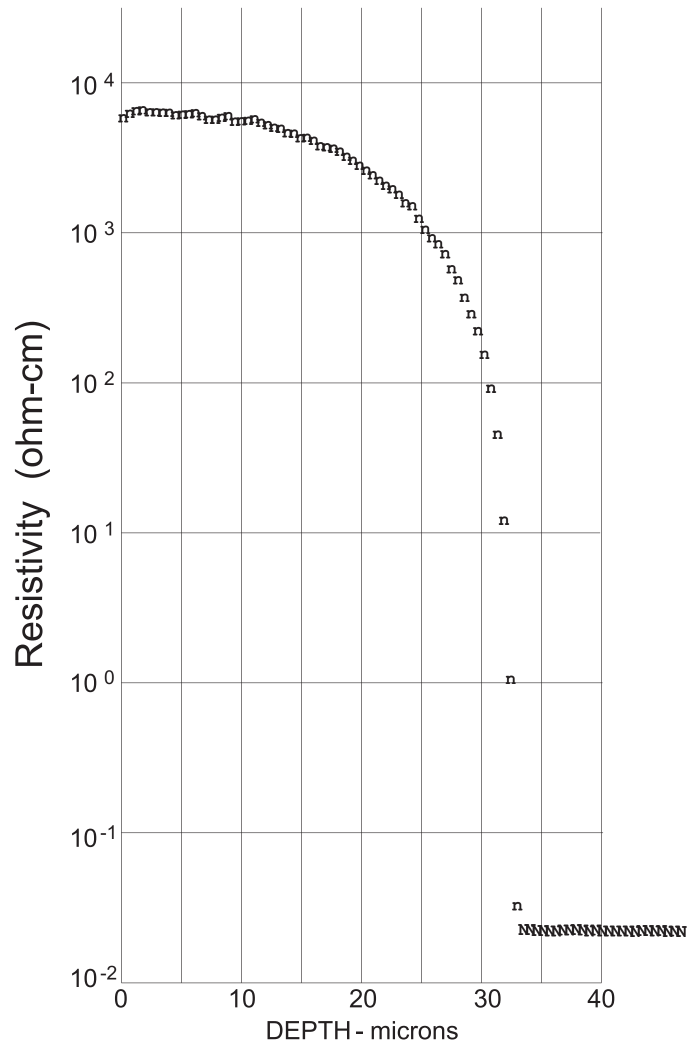
Data Reduction



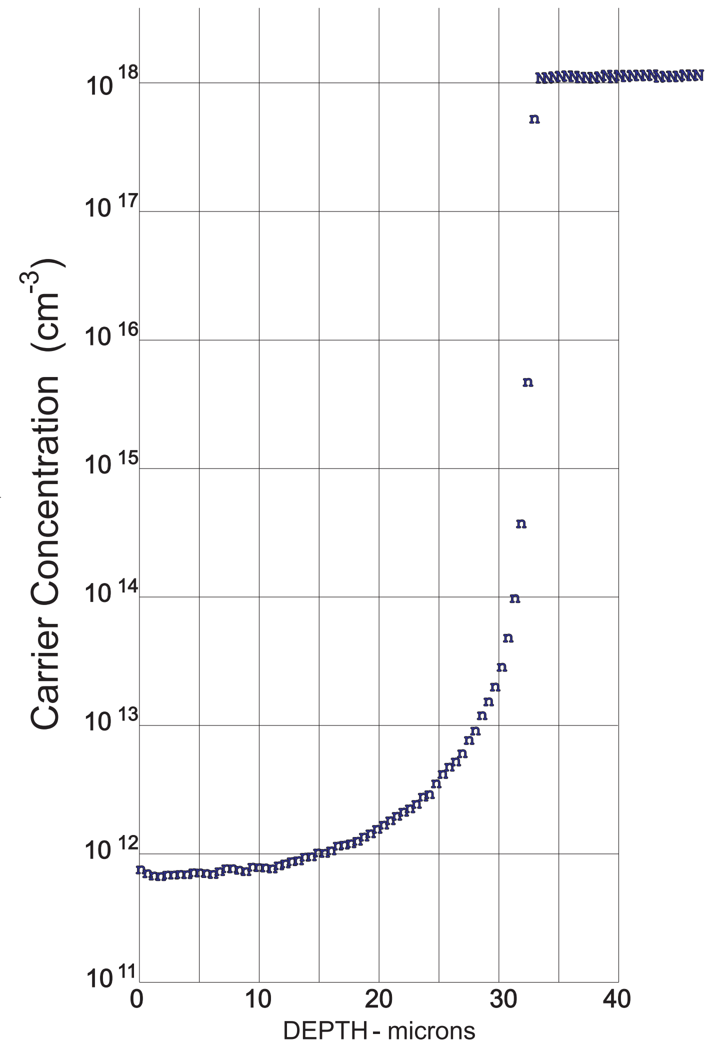
"Raw Data"

Resistivity Plot

High Resistivity Epi (continued)

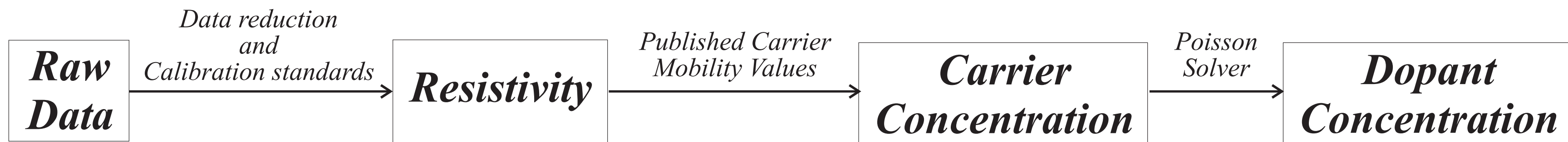


Carrier Concentration Calculated Using Published Carrier Mobility Values

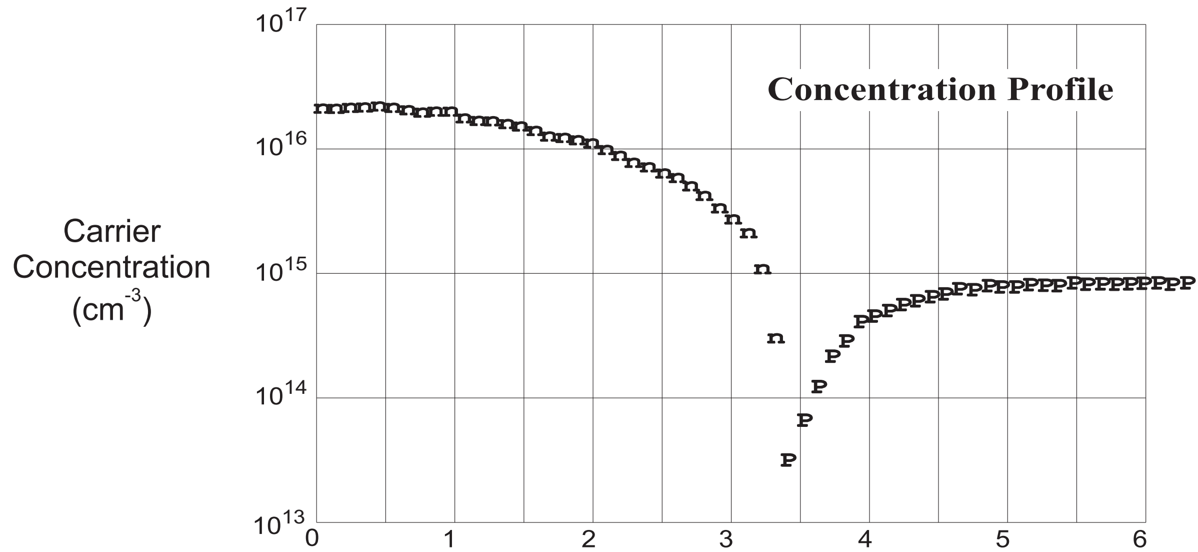


Resistivity → Carrier Concentration

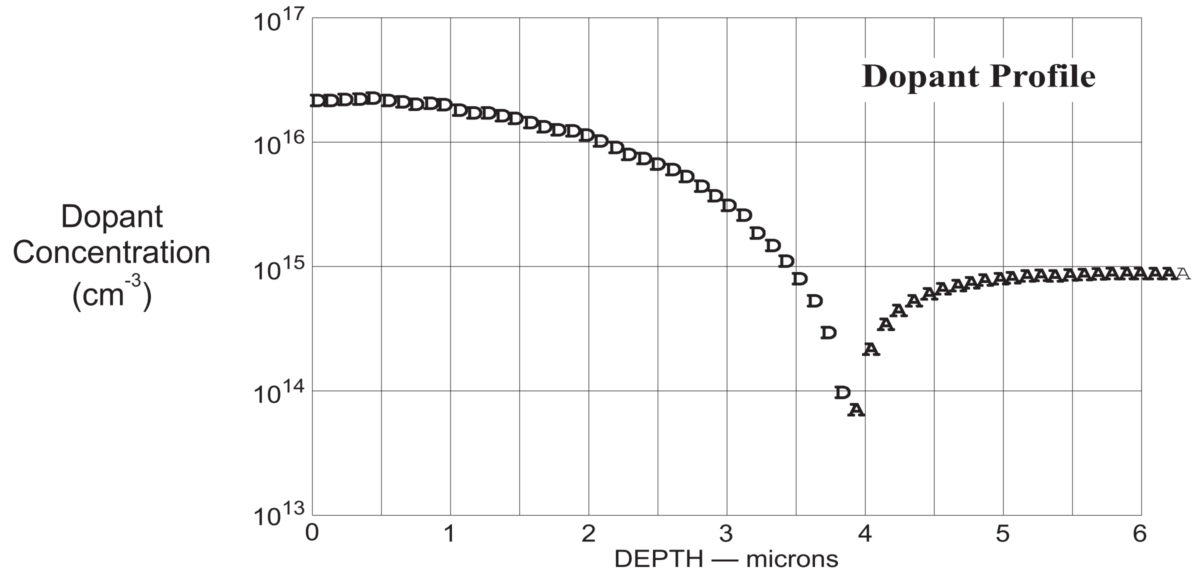
SIMPLE CARRIER CONCENTRATION PROFILES CAN BE CONVERTED TO DOPANT PROFILES USING OUR POISSON SOLVER



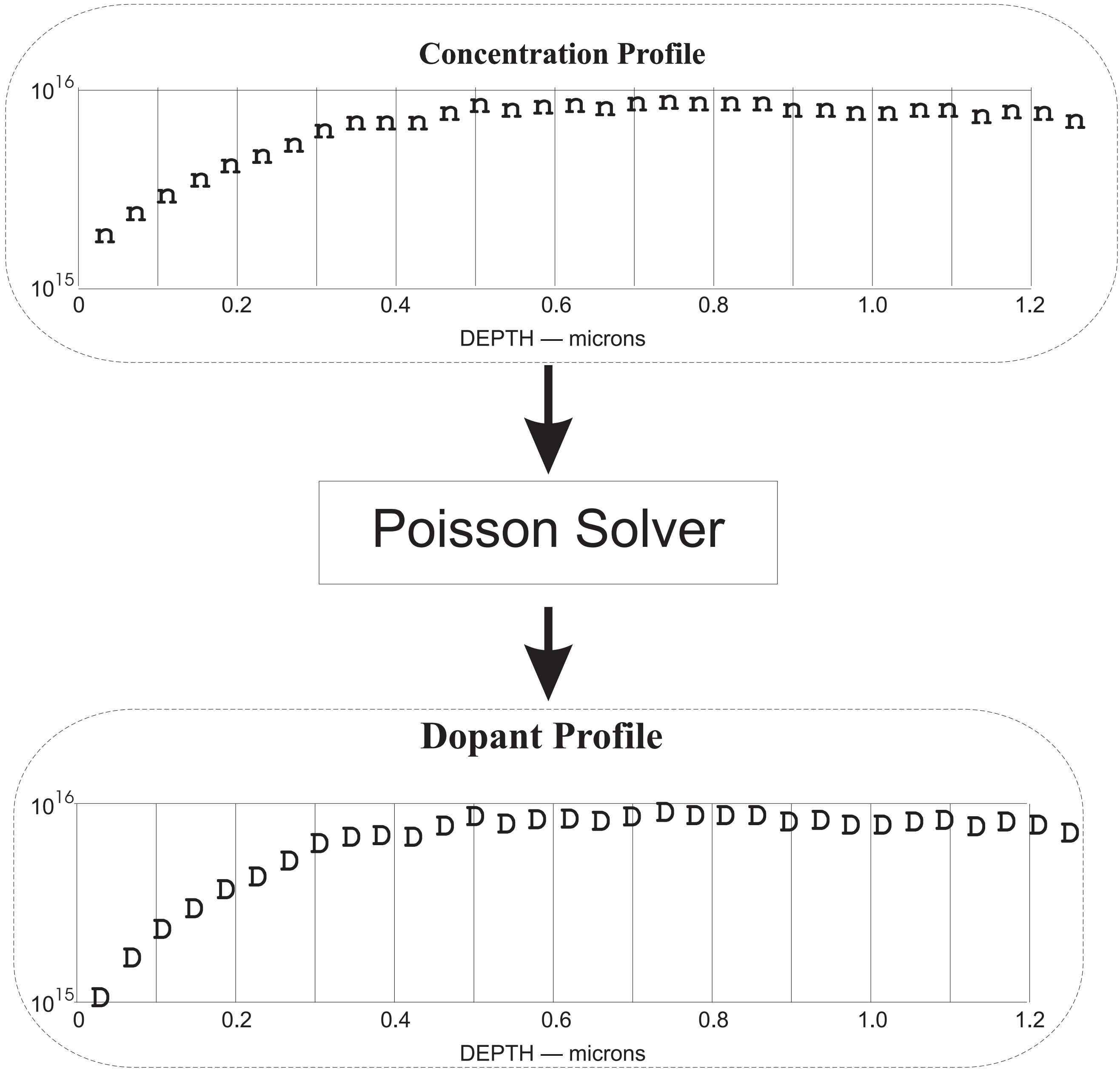
Simple Carrier Concentration Profiles can Easily be Converted to Dopant Profiles using our Poisson Solver



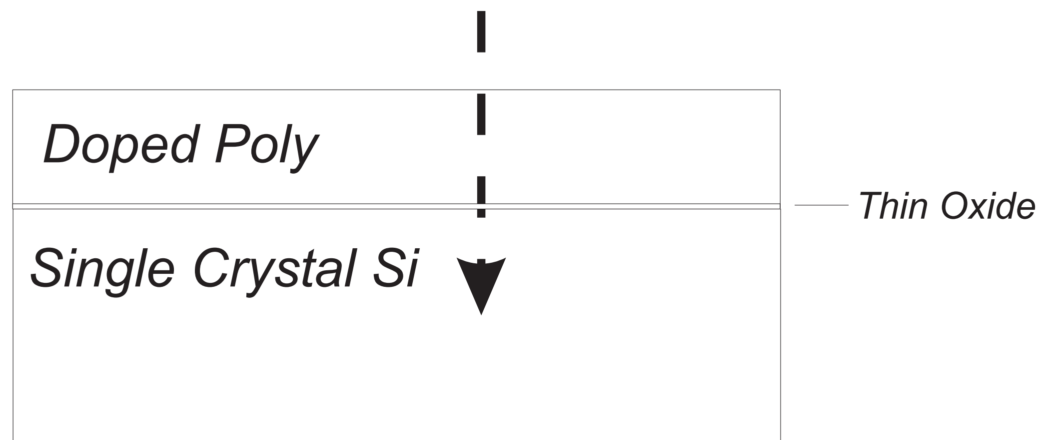
Poisson Solver



Simple Carrier Concentration Profiles can Easily be Converted to Dopant Profiles using our Poisson Solver



A "POLY" PROFILE



SIMS and SRA for 1e16 B^{11} implant into poly/oxide/substrate

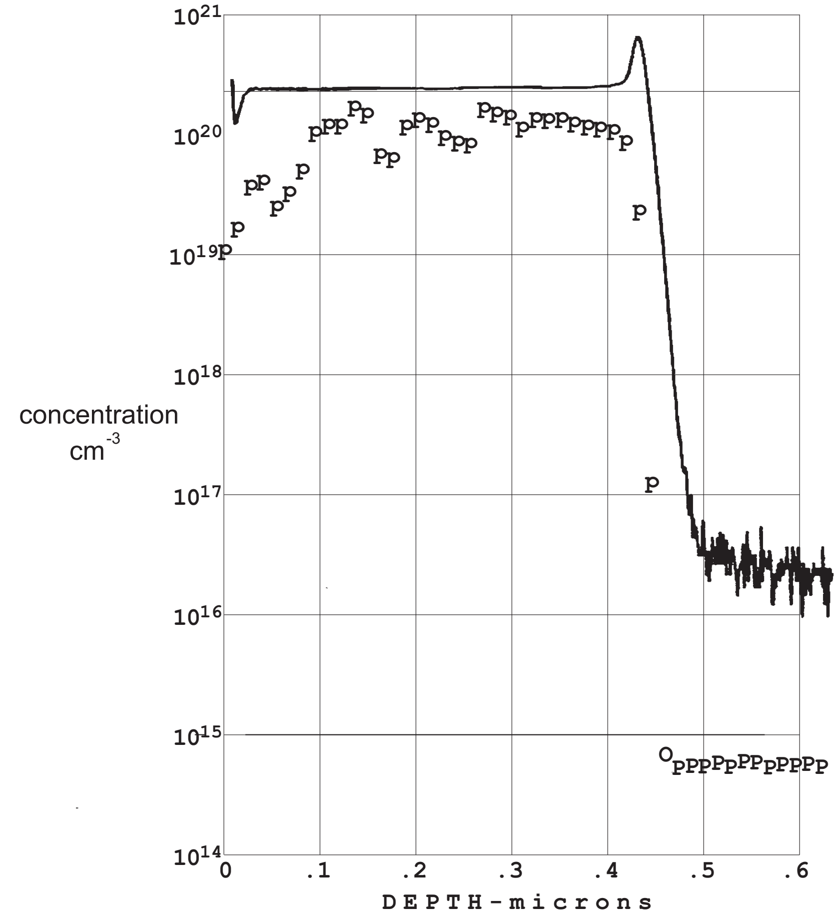
SRA calculated sheet: 26 Ω/sq

Four-point probe: 26.3 Ω/sq

SIMS determines atomic concentration.

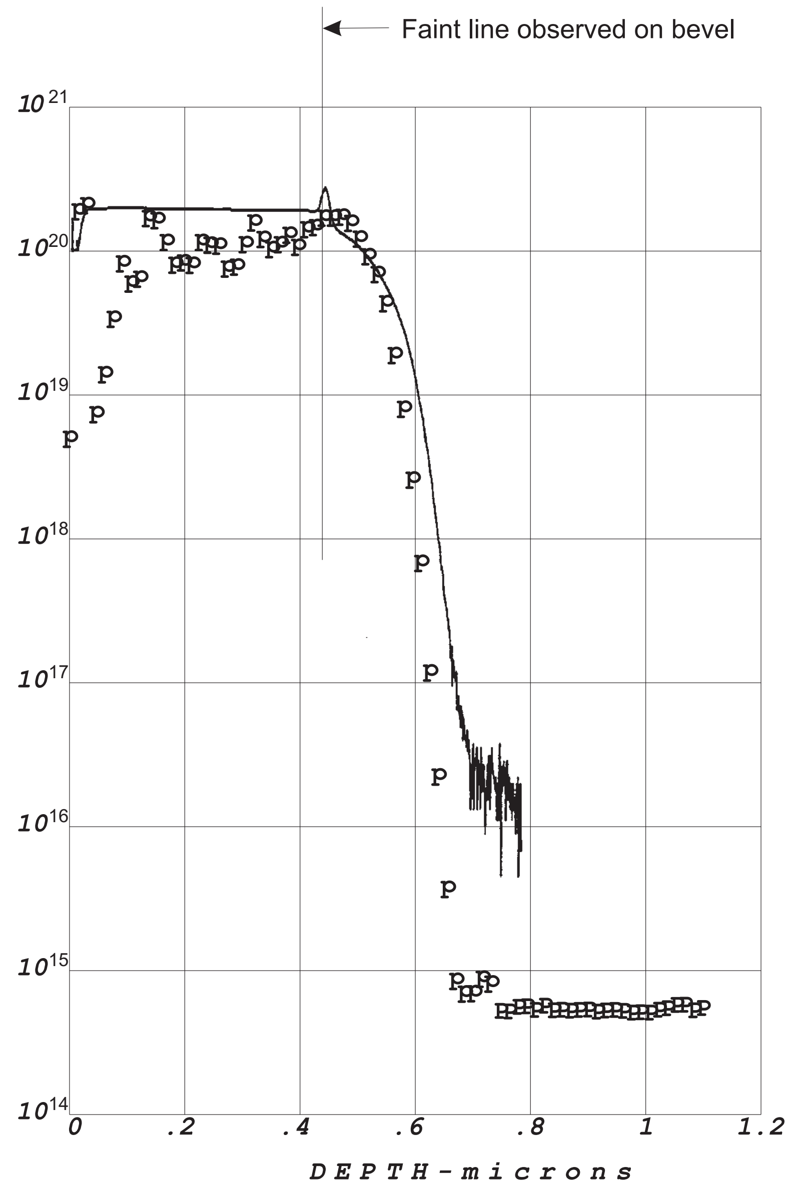
SRA determines resistivity.

Carrier concentration can be calculated if carrier mobility is known or assumed. We use the bulk carrier mobilities from Thurber, Mattis, and Liu, **NBS SP 400-64.**



After: Raicu *et al*, Talk:C6.5 MRS meeting, April 1990.

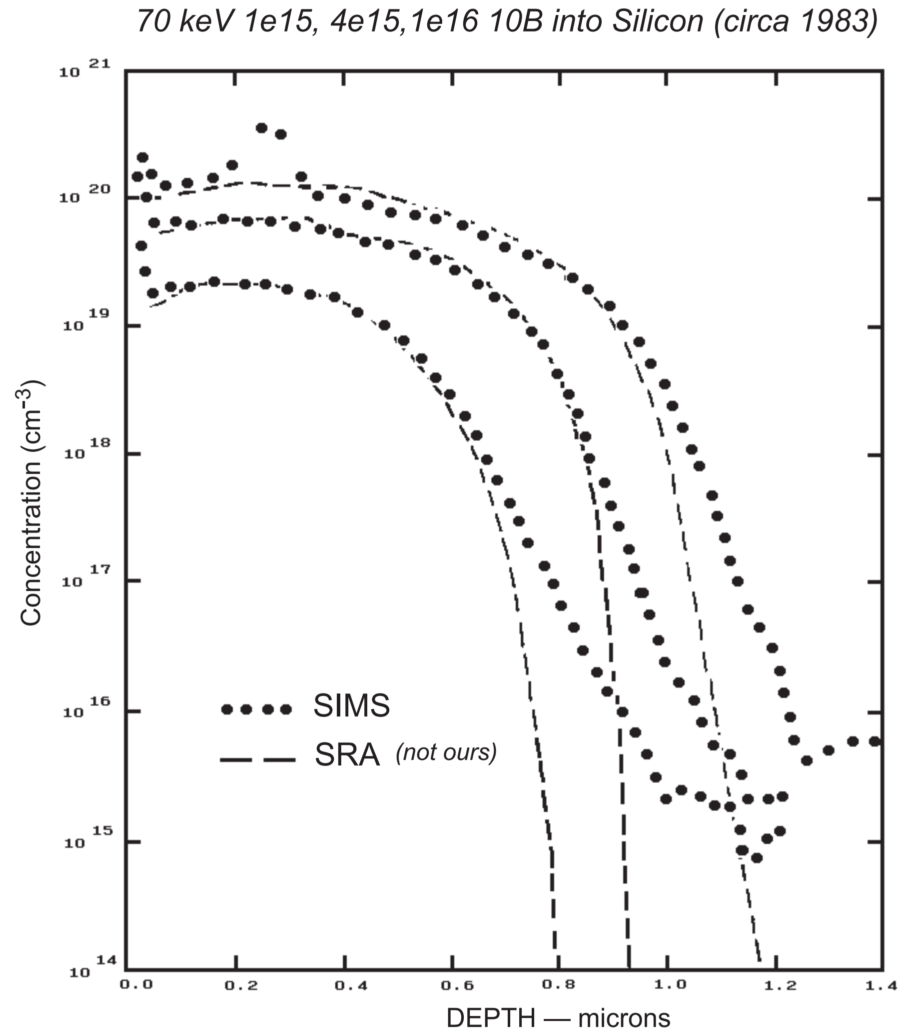
SIMS and SRA for 1e16 B^{11} implant into poly on substrate



After: Raicu *et al*, Talk:C6.5 MRS meeting, April 1990.

SIMS Typically Reports Greater Depth in the Tail Region of B Diffusions. In the Following Example, Boron was Implanted into Single-crystal Si.

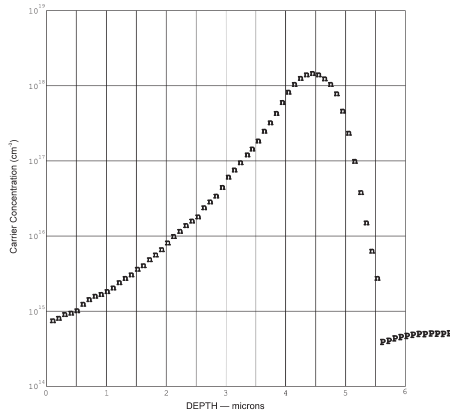
70 keV 1e15, 4e15,1e16 10B into Silicon (circa 1983)

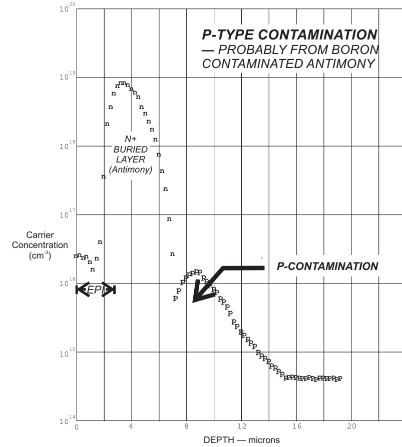


From : James Ehrstein *et al*, ASTM Special Technical Publication **850**, D. C. Gupta, editor, p. 415.

Some of Our All-Time Favorite Profiles

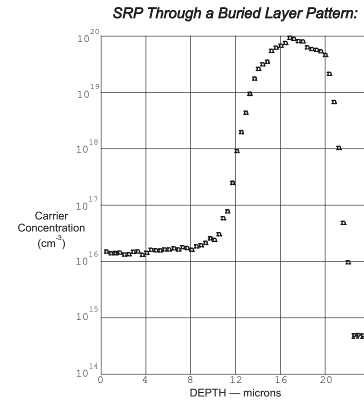
11 MeV Arsenic Implant



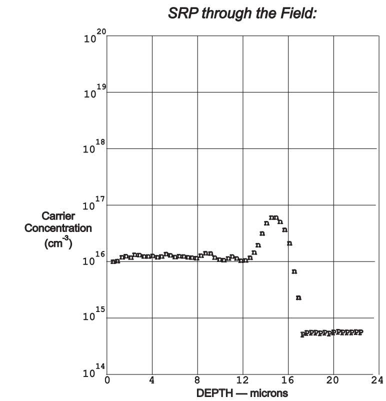


Arsenic Autodoping During Epitaxial Deposition

SRP Through a Buried Layer Pattern:

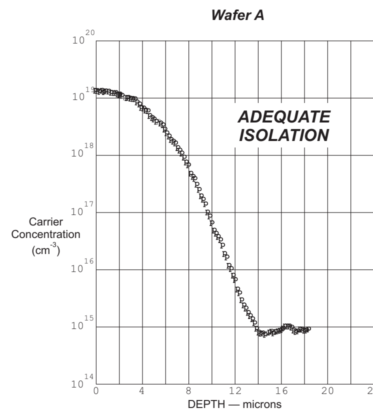


SRP through the Field:

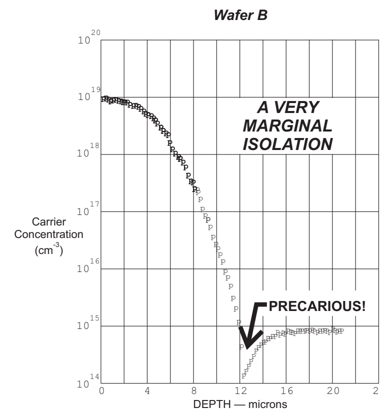


P+ Isolation Diffusion into N-Epi

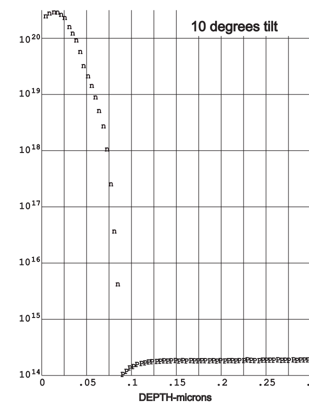
Wafer A

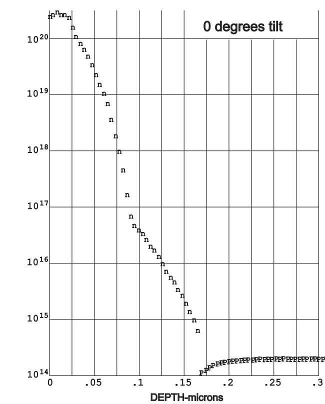


Wafer B

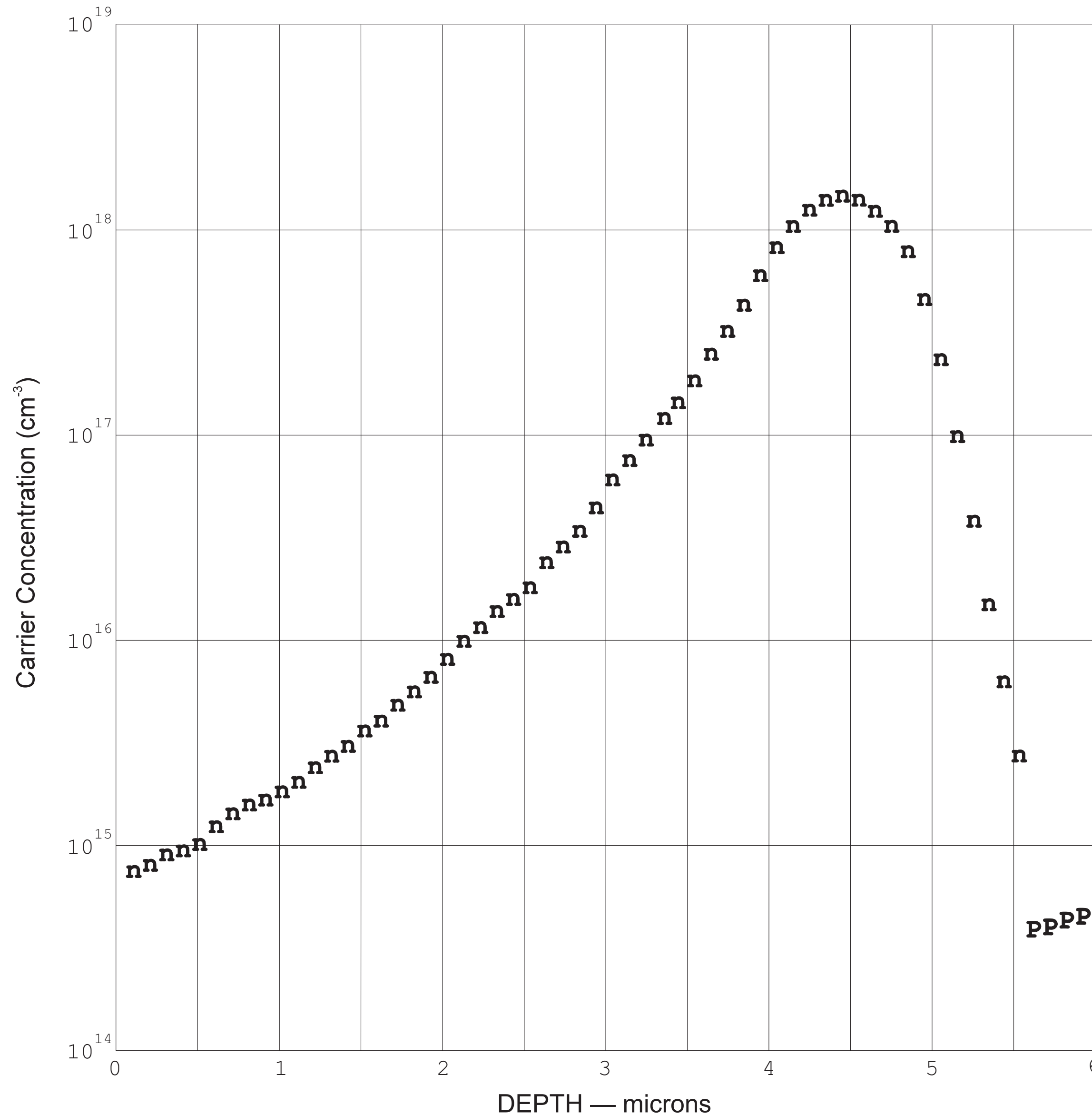


Ion Implant Channeling





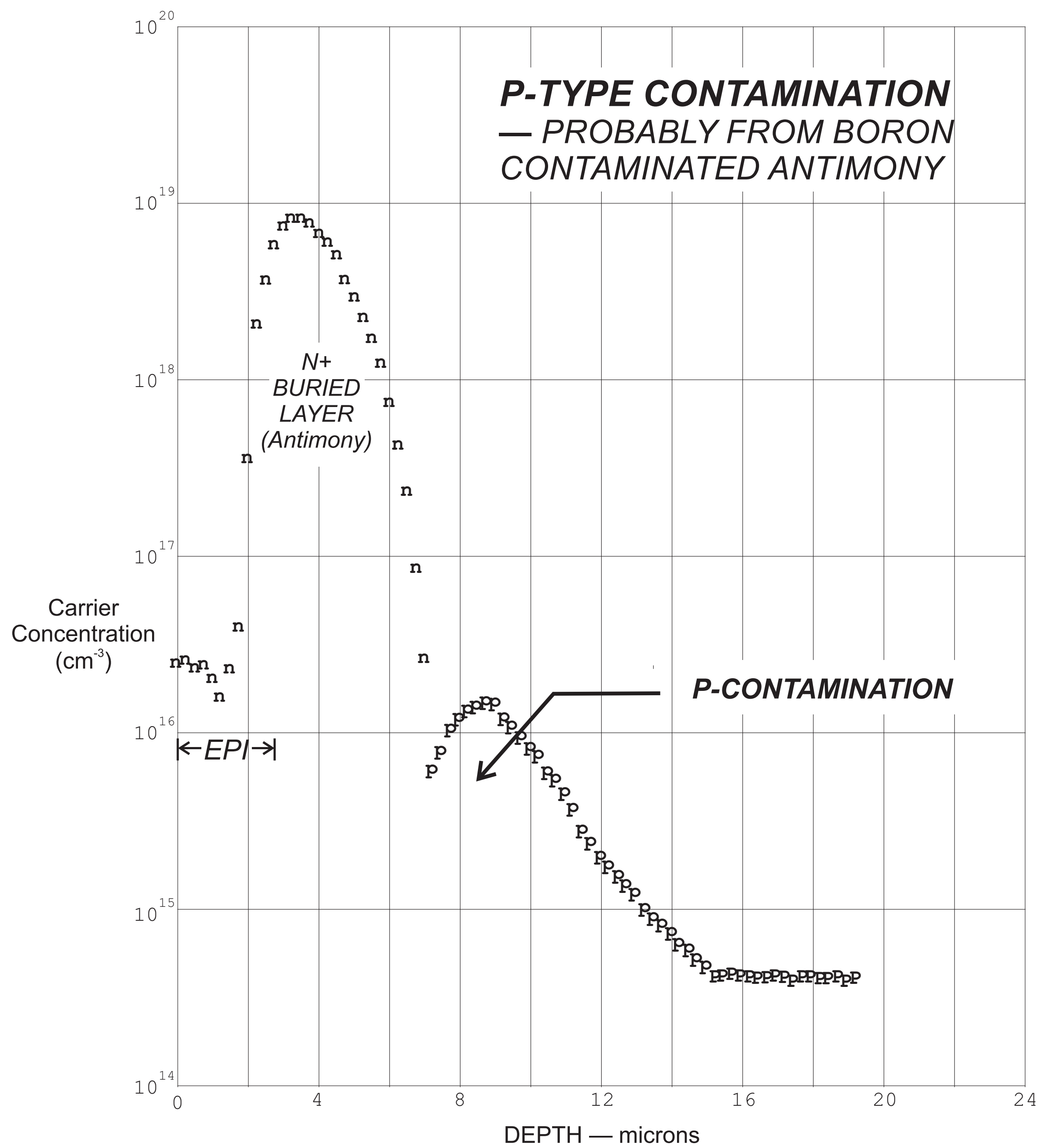
11 MeV Arsenic Implant



"The implantations were carried out using the facilities of the Lawrence Berkeley Laboratory. 11 MeV beams were obtained from a dynamatron with a 2.2 megavolt terminal. The ion source is a conducting crystal of gallium arsenide from which arsenic ions in the 5+ charge state were sputtered and extracted into the accelerator column."

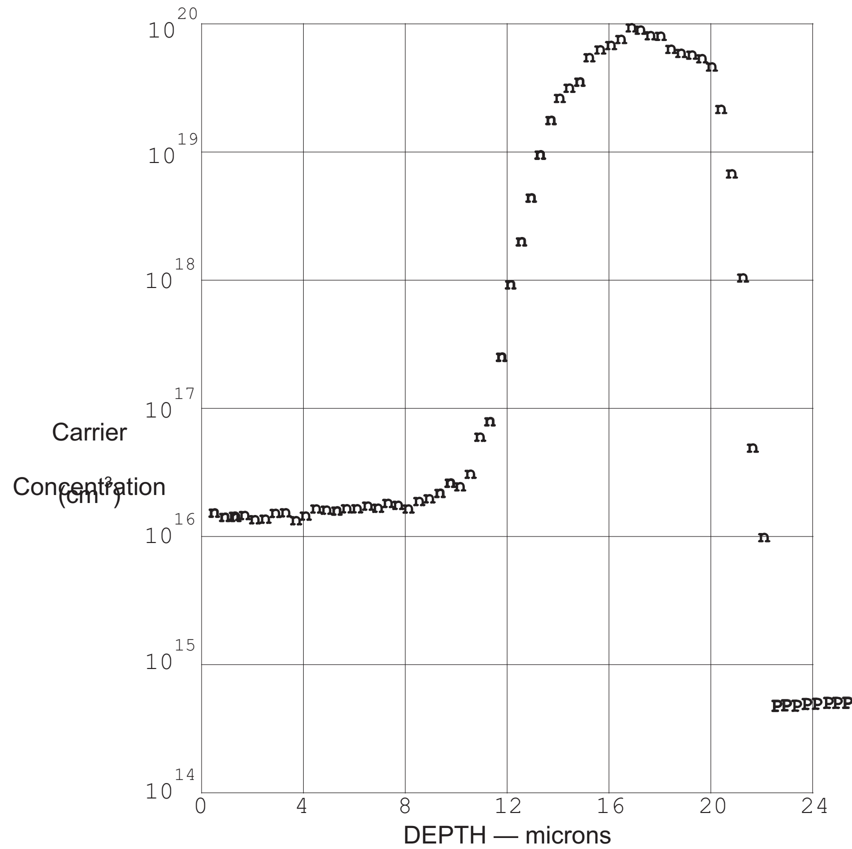
From *Megavolt Arsenic Implantation into Silicon,* a paper presented at the 1982 International Conference on Metallurgical Coatings and Process Technology by P.F. Byrne, N. W. Cheung, and D.K. Sadana, University of California, Berkeley.

Many thanks to Peter Byrne for permission to reproduce and disseminate this very impressive profile.

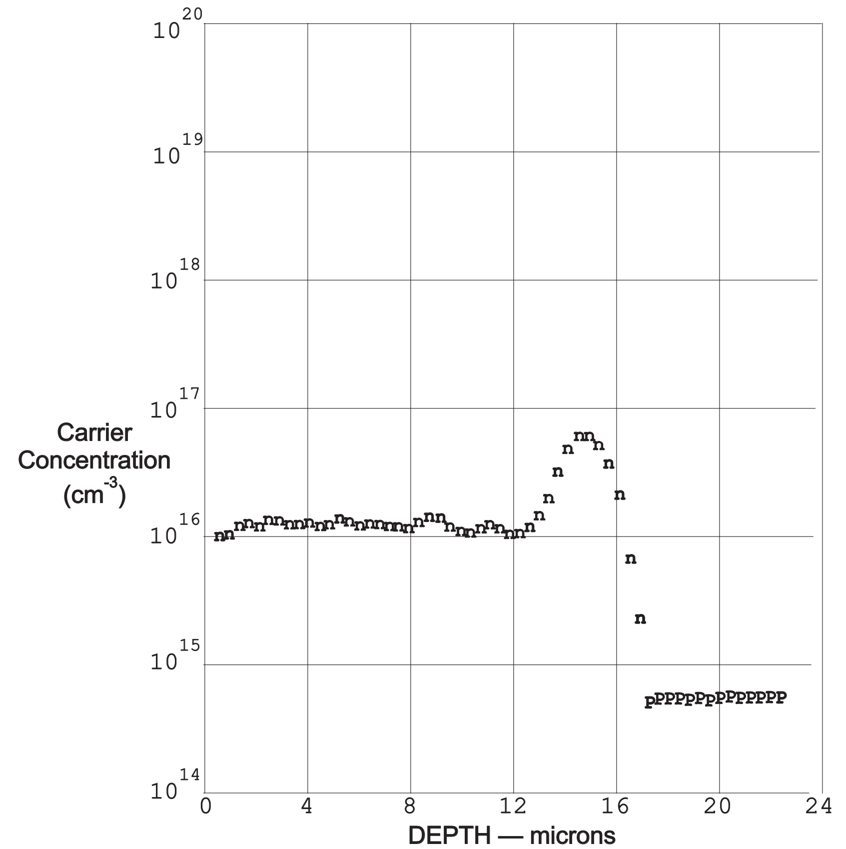

P-TYPE CONTAMINATION
— PROBABLY FROM BORON
CONTAMINATED ANTIMONY
N+
BURIED
LAYER
(Antimony)
P-CONTAMINATION
EPI
Carrier
Concentration
(cm-3)
DEPTH — microns
0
4
8
12
16
20
24

Arsenic Autodoping During Epitaxial Deposition

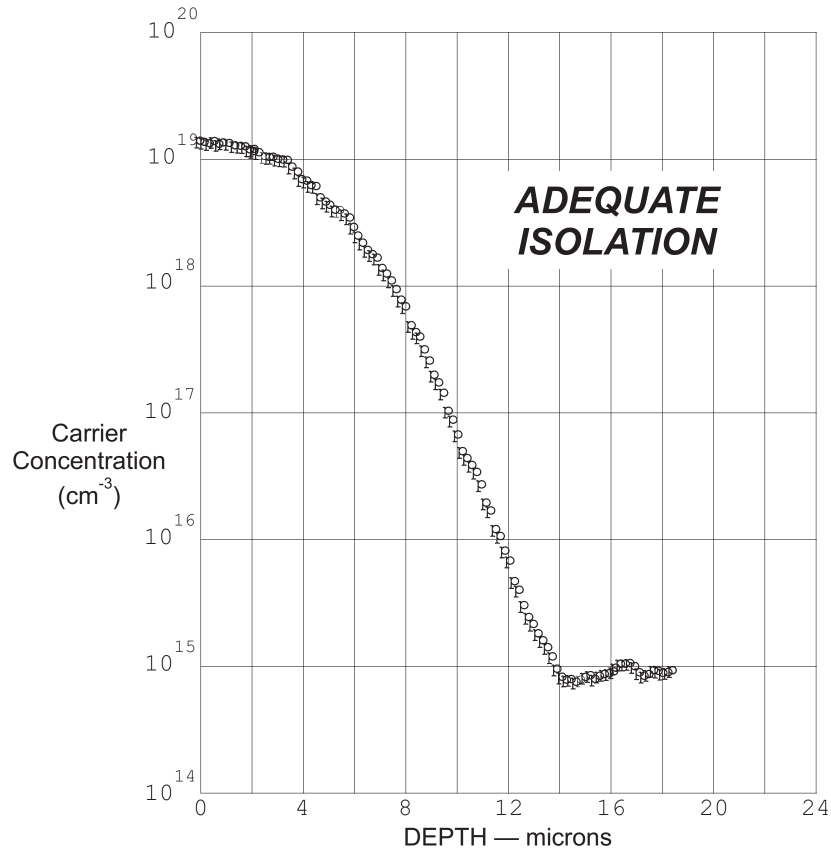
SRP Through a Buried Layer Pattern:

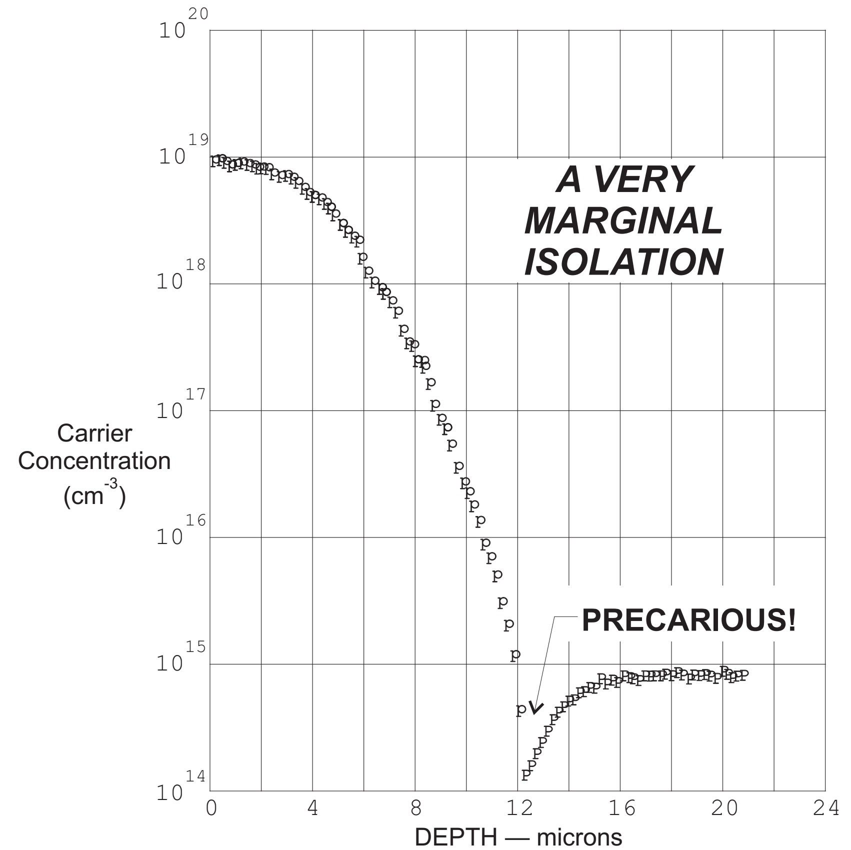


SRP through the Field:

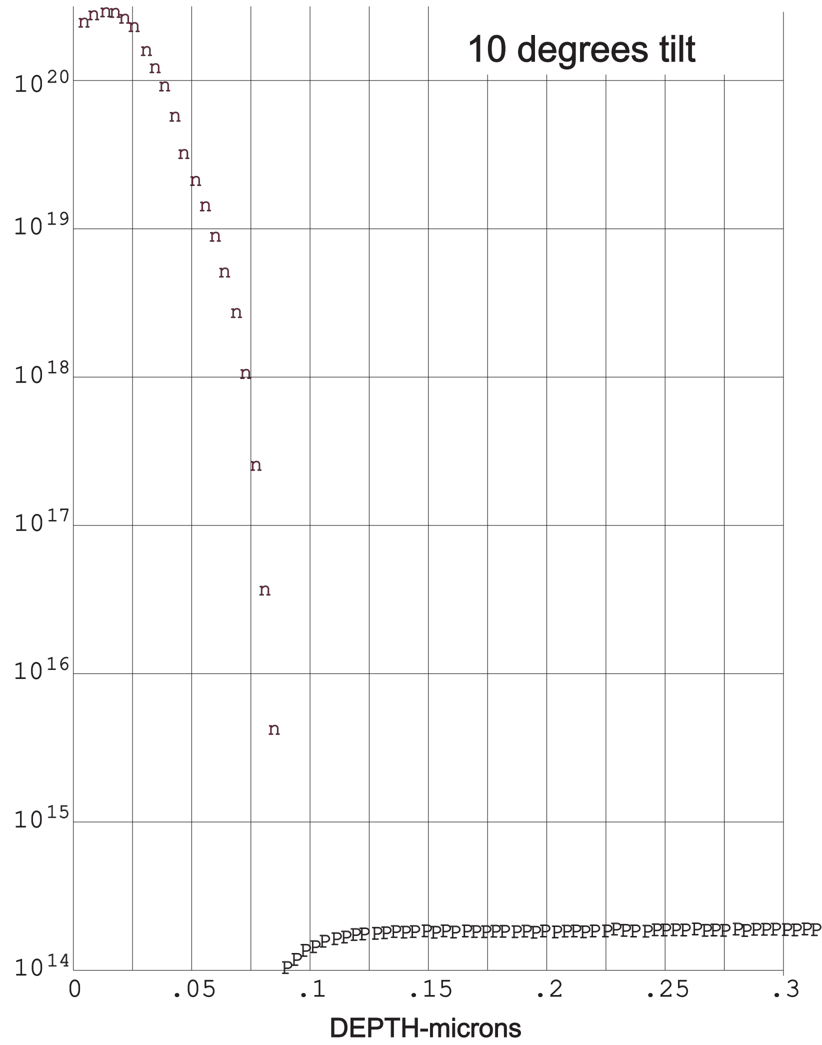


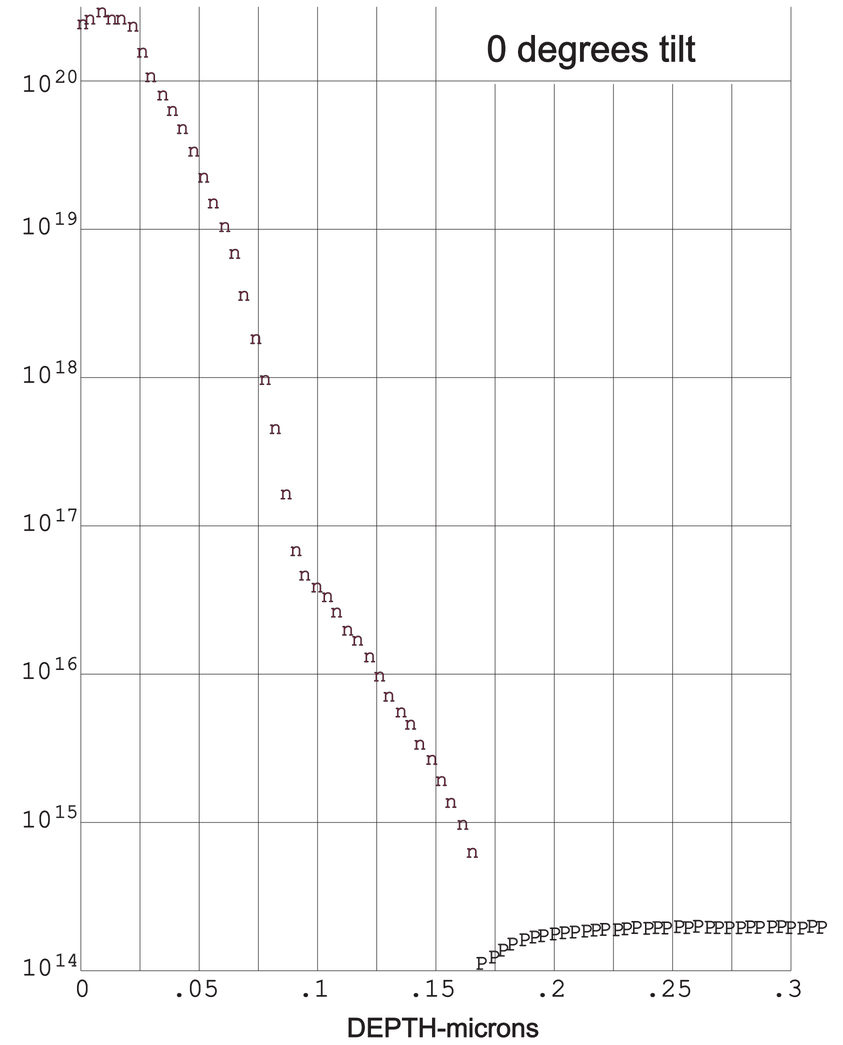
P+ Isolation Diffusion into N-Epi



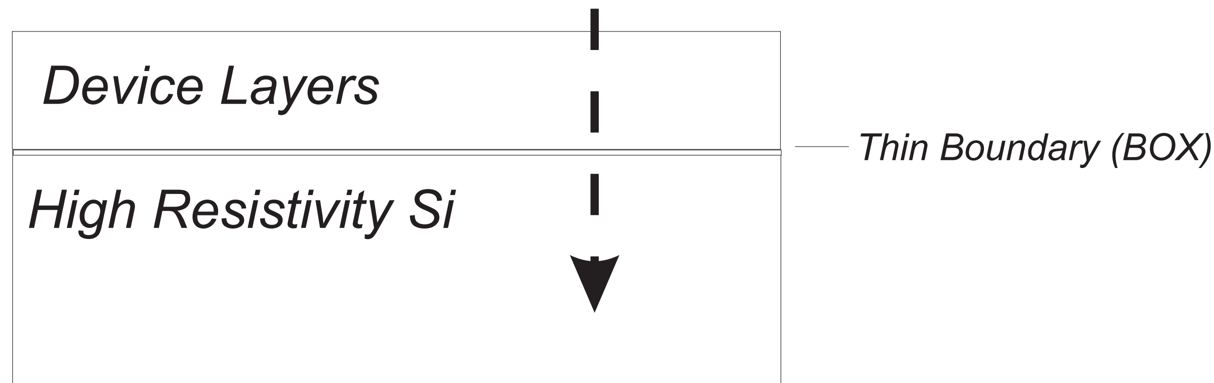


Ion Implant Channeling



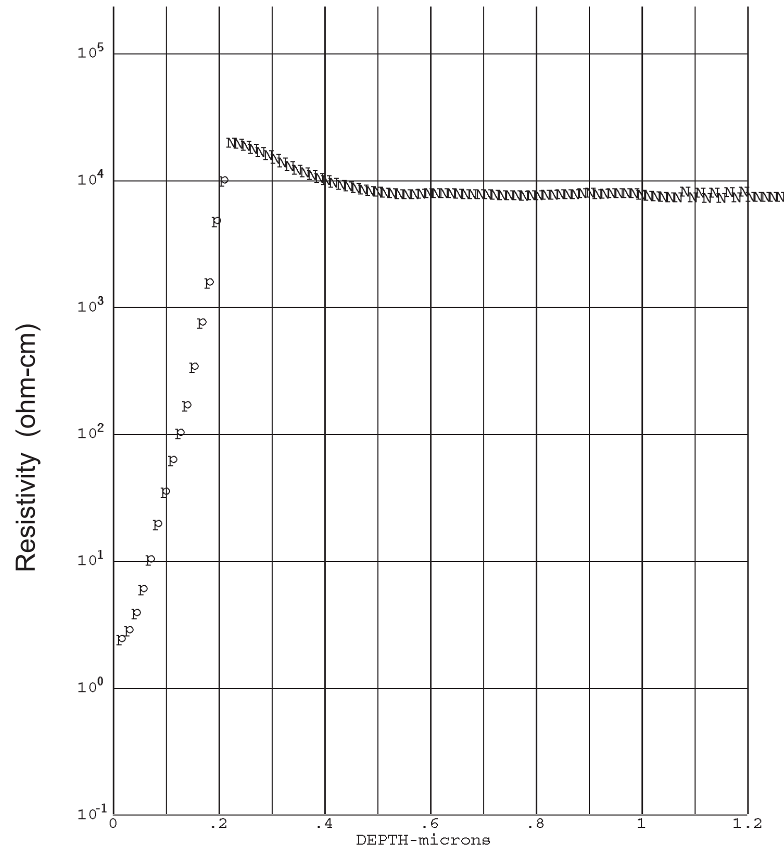


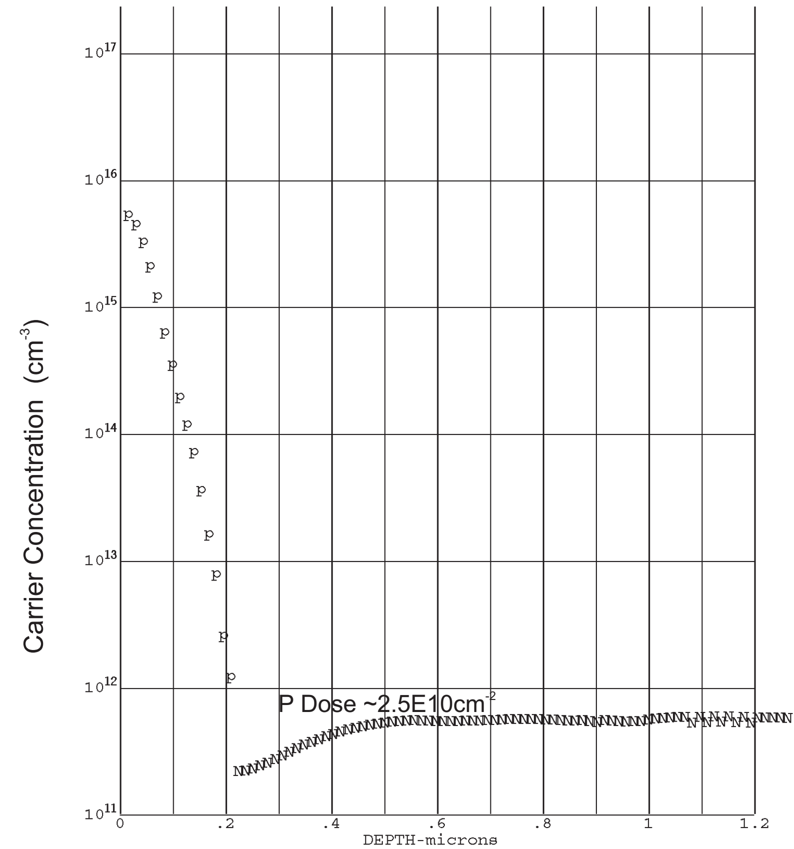
HIGH RHO SUBSTRATES



High Resistivity Silicon, found under GaN or Si/BOX device layers, is N or P type and over 3000 ohm-cm!

GaN on High Rho Substrate

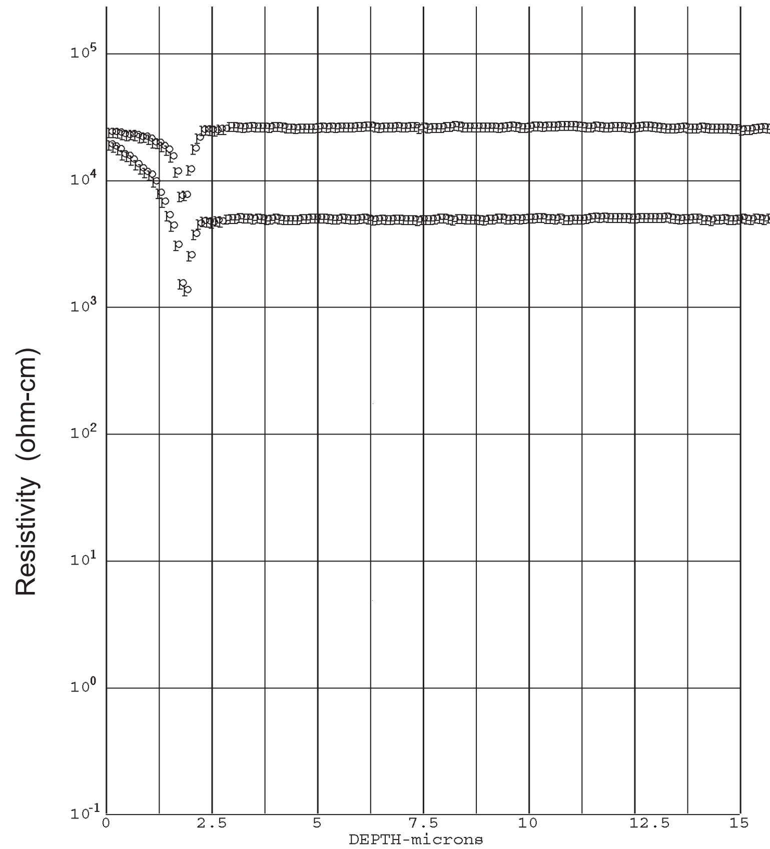


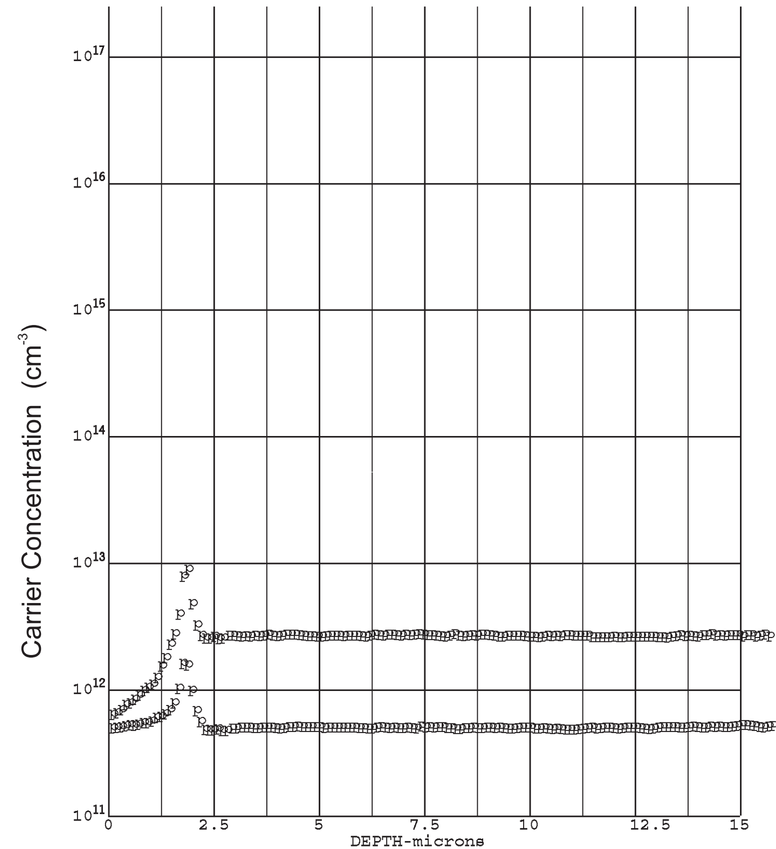


While SRP or 4PP can NOT measure GaN layers, we CAN measure the silicon substrates under III-V compounds. GaN devices typically have 1.5-2μms of GaN devices on top of a high resistivity silicon substrate. Our challenge is to bevel through the GaN and have adequate resolution for the gallium leaking into the substrate. We sometimes require angles that are steeper than desired due to the “order of magnitude” depth rule.

Note: GaAlN can diffuse an order of magnitude deeper thanks to the aluminum. Much easier to do!

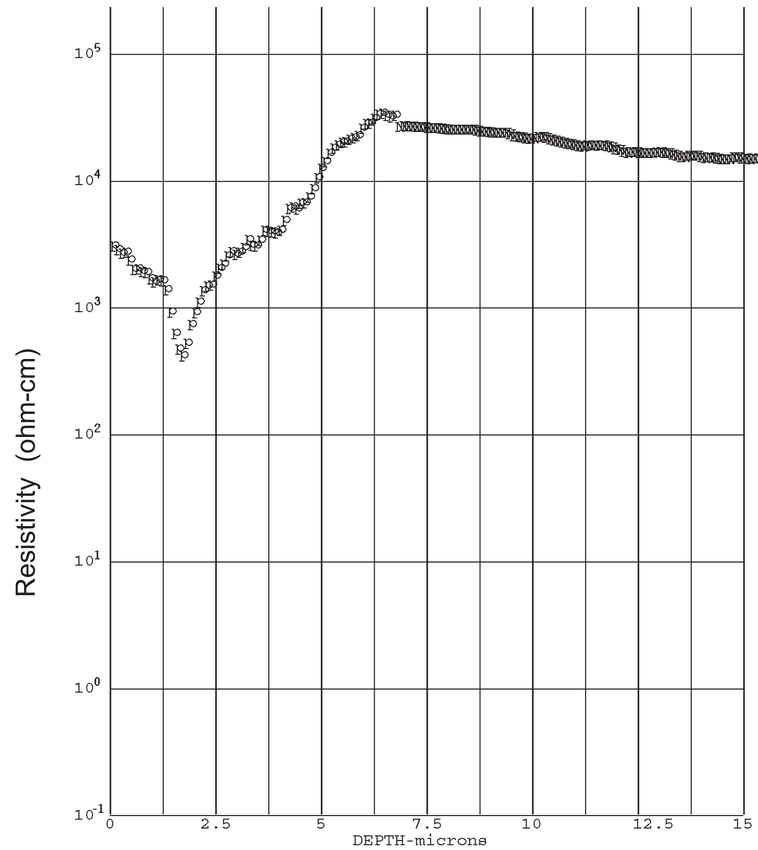
SOI on High Rho Substrate

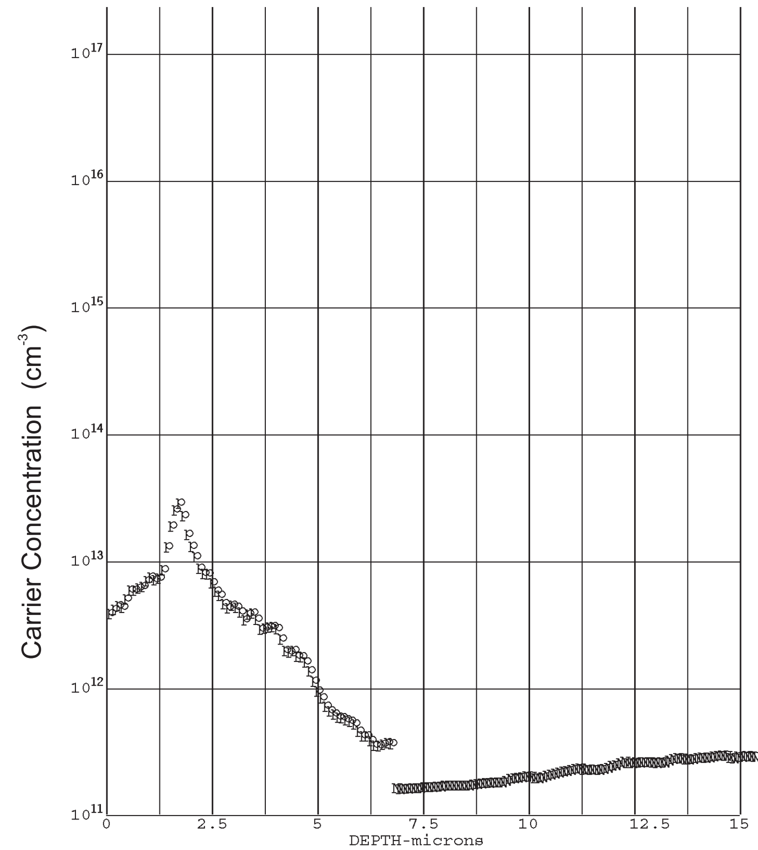




SRP or 4PP can also measure SOI samples. SOI devices typically have a thin silicon device layer over BOX over 1.5-2µms of poly, with a trap implant, on top of high resistivity silicon substrates. In the early 2010's, we started seeing substrates with resistivities over 5Kohm-cm. We were impressed! The two profiles shown here are 5K and 25K ohm-cm. Both of these received the same poly and trap implant below the BOX. You can see how the levels get back to almost the same resistivity/concentration at the surface.

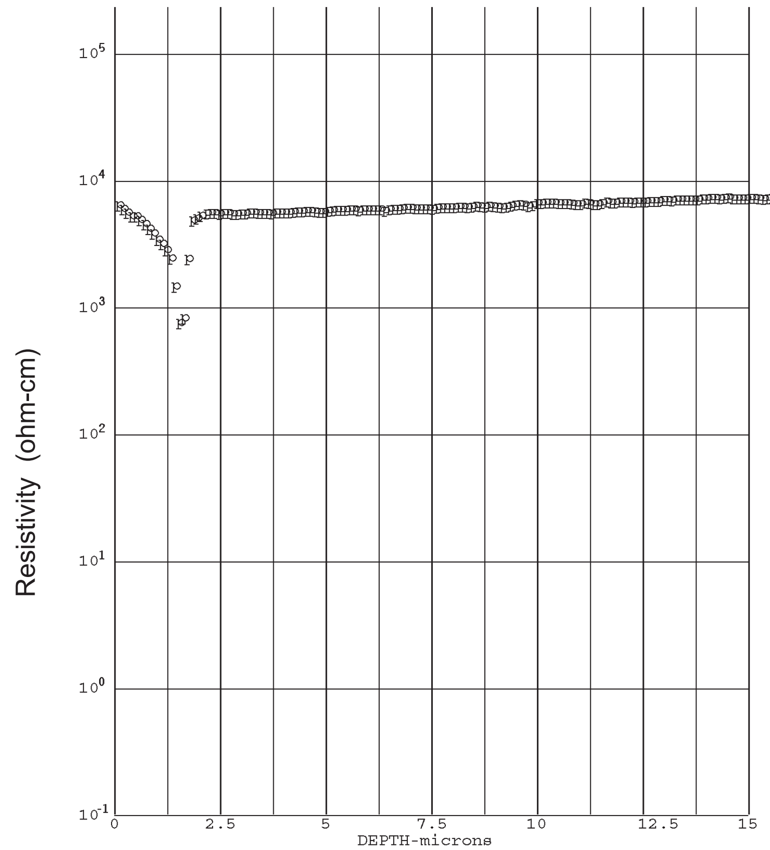
SOI on High Rho Substrate





This profile also starts at the BOX/poly interface. It has a much more obvious type change at 6.75µm depth, including the poly trap. The P-type inverting to N-type is more difficult to confirm with just the hot probe due to the high resistivity. The shape of the profile, including the cusp is an indicator that the type changed.

SOI on High Rho Substrate

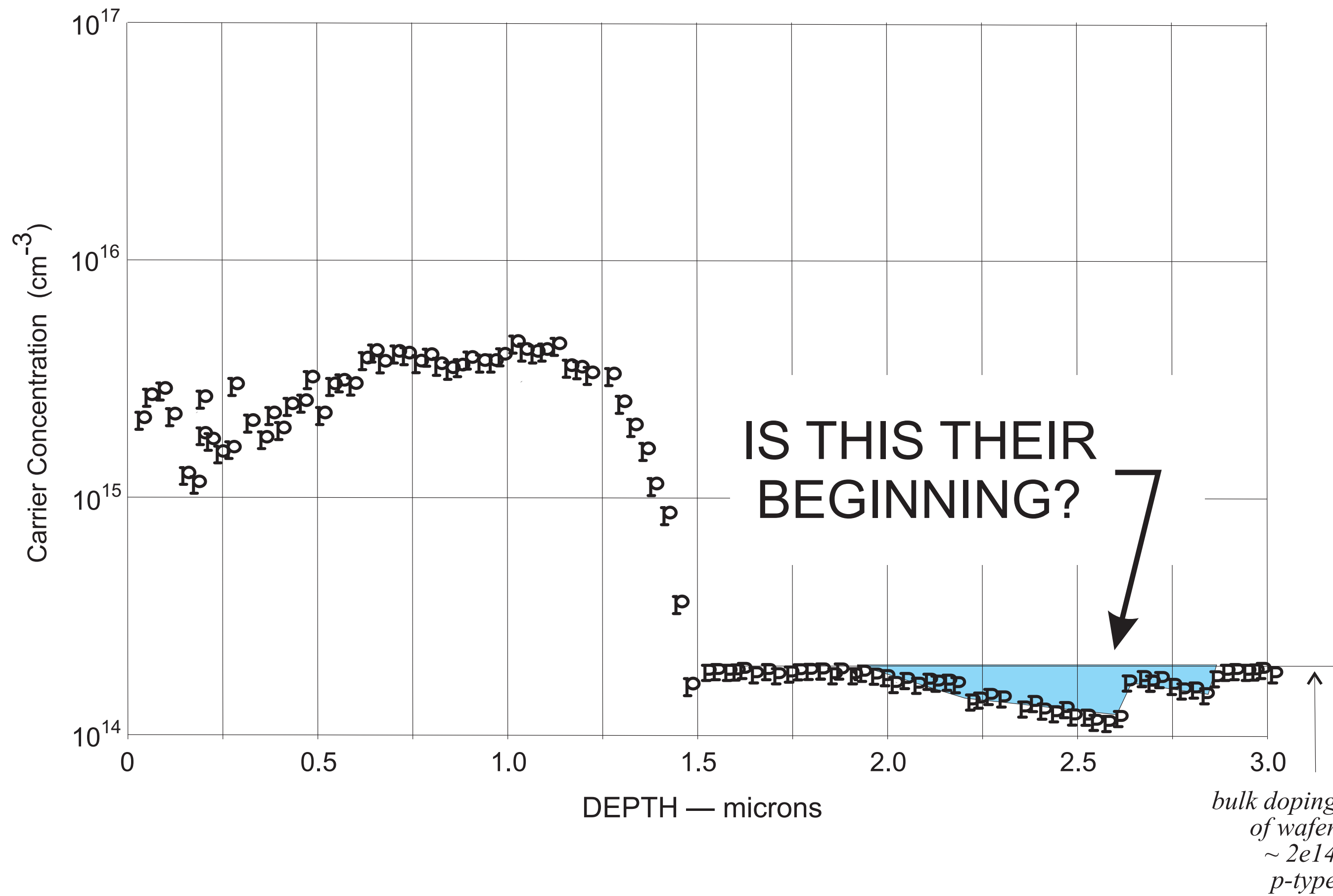


These profiles start at the BOX/poly interface. Notice how the 5Kohm-cm substrate starts climbing on the profile on the left. Suspicious! To investigate, the right profile was run much deeper and shows that the resistivity continues to climb until ~90µm where the P-type inverts to N-type before dropping back down to about 5Kohm-cm. The bumpiness of the resistivity, after 90µm depth, is similar to what we see with oxygen donor wafers.

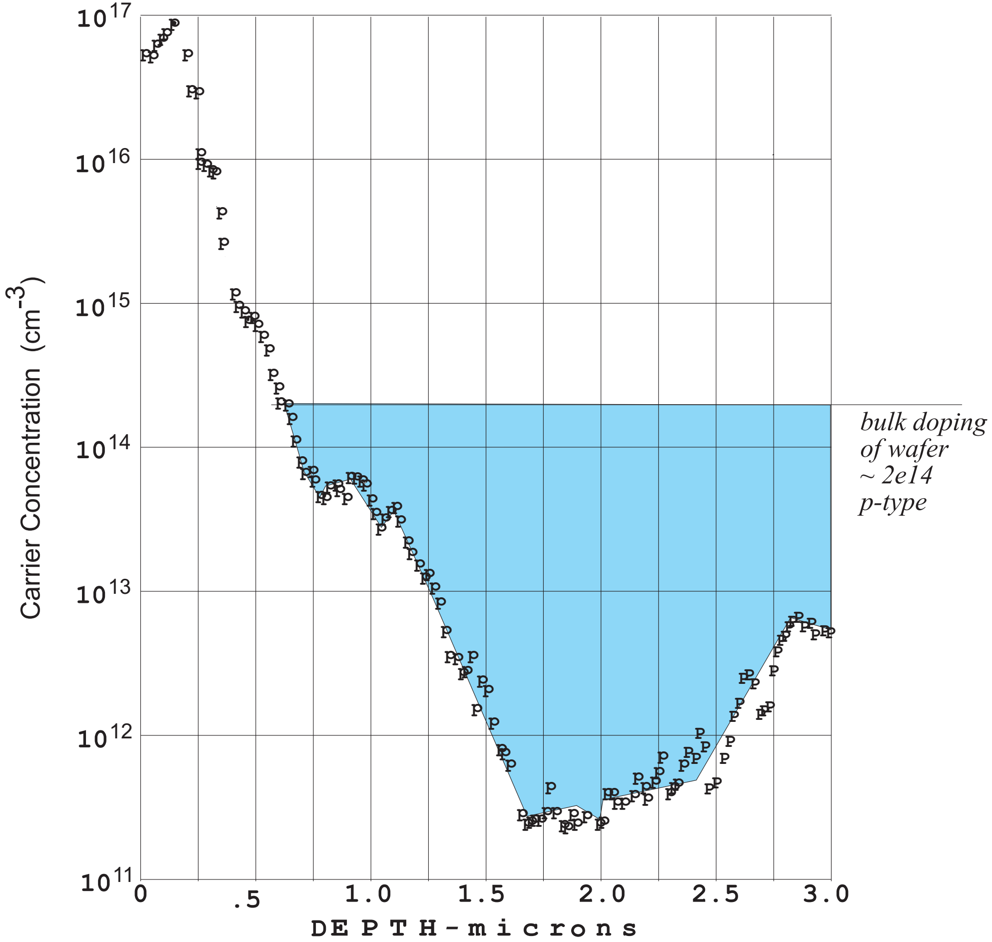
Thermal Donors

Silicon Containing Dissolved Oxygen
Processed Long Enough at ~ 400°C
Forms an Entity that DONATES Electrons
(i.e. Acts N-Type)

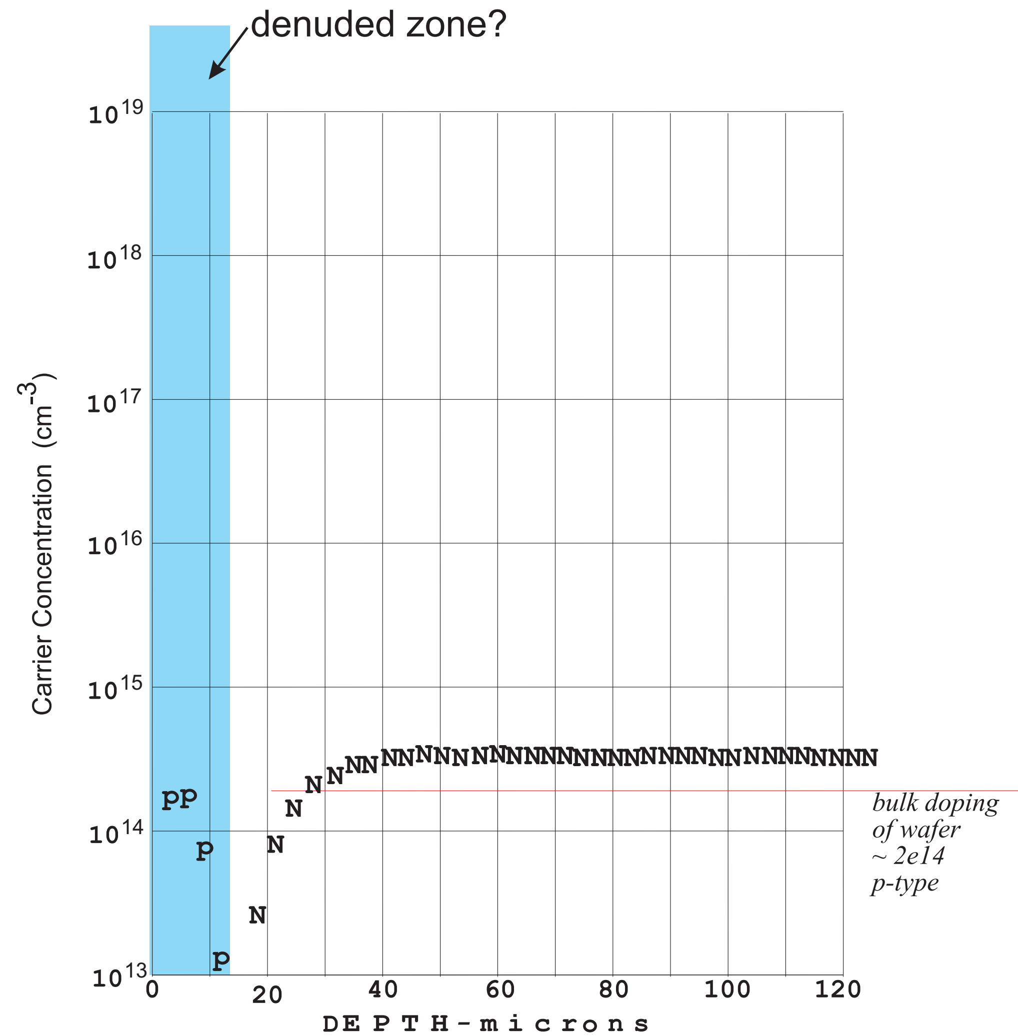
Looking for Thermal Donors



Thermal Donors — A More Severe Case

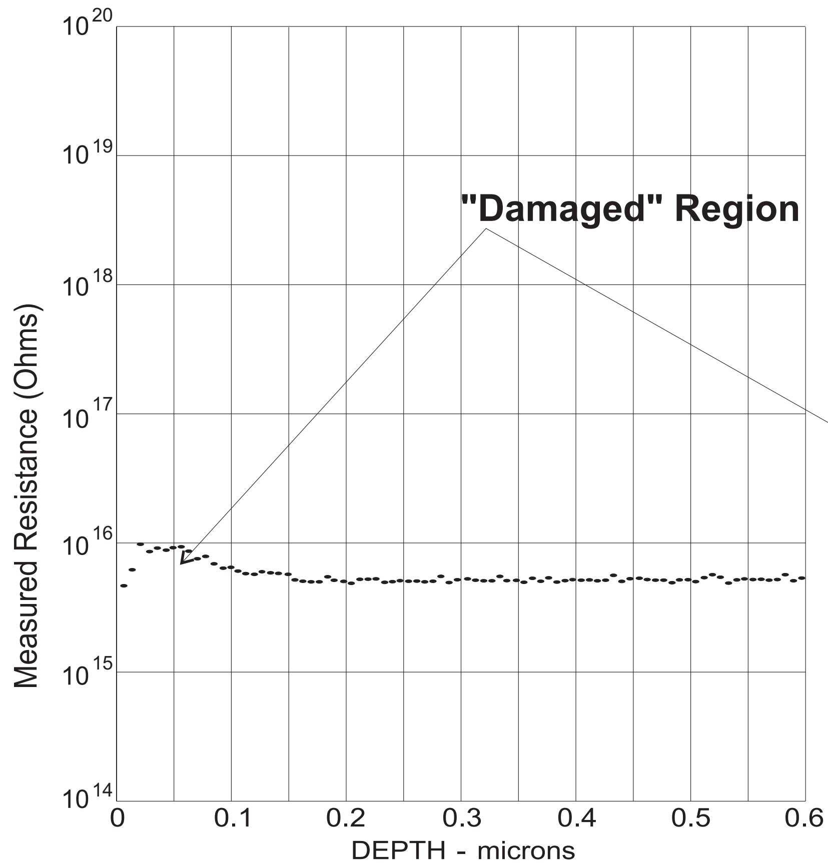


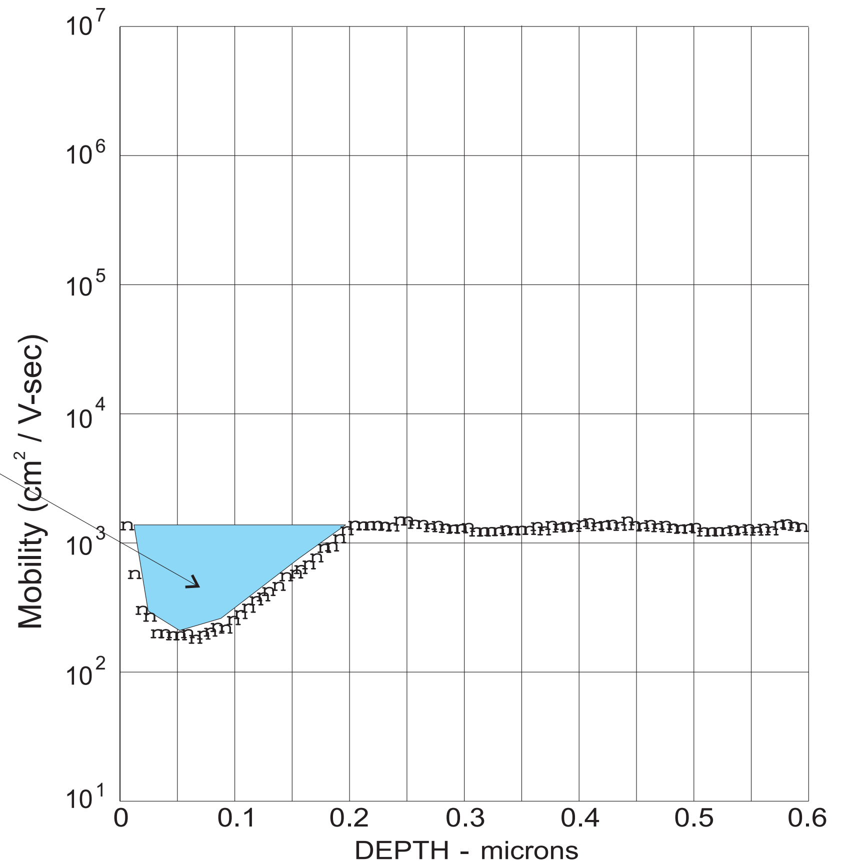
Thermal Donors — An Extreme Case



Unannealed Implant

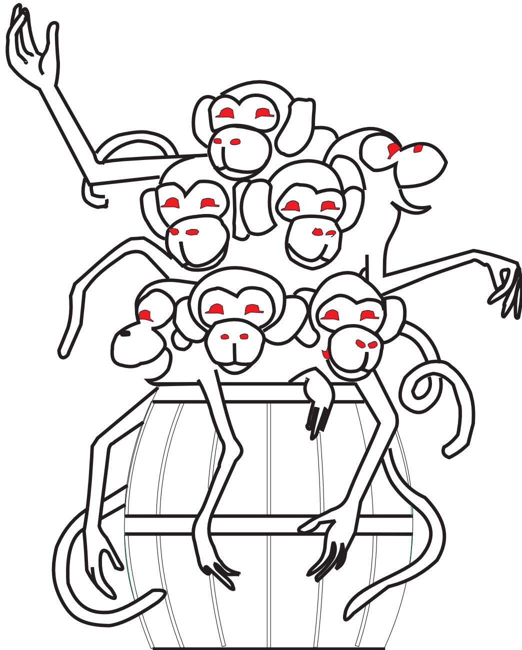
N-type implant into 1e16 cm^{-3} N-type background. Since the implant wasn't activated, SRA senses the mobility change in the damaged area.





In Closing...

- *Please visit us and take the tour*
- *SRA is useful whenever the doping of silicon is of concern*
- *Web page: www.solecon.com*



Best wishes from the folks at Solecon Labs.