Measurement of Strain Enhanced Mobility

JTG Meeting @ SEMICON West

July 14, 2011

Measurement of Strain Enhanced Mobility

Differential Hall Effect measurements represent a unique method of measurement for USJ’s

1. Direct measurement of mobility profile, μ(x)
2. Direct measurement of resistivity profile, ρ(x)
3. Determination of carrier distribution, n(x)

$$n(x) = \frac{1}{\mu(x) \cdot \rho(x) \cdot q}$$

$$q = electron\ charge$$

Calculation of Internally Applied Strain

$$\varepsilon_x = -\beta c$$

where β= the solute lattice concentration or expansion coefficient.
ε_x= biaxial strain on planes parallel to the surface.
c= concentration of foreign atoms on lattice sites.

Table below lists Pauling's single bond covalent radii.

$$\beta = \frac{R_x - R_{Si}}{R_{Si} \cdot N}$$

where R_{Si}= covalent radius for silicon
R_x= covalent radius for foreign atoms
N= density of lattice sites, 4.99E22 cm-3

for B, β=-5.77E-24 cm-3.

Element	Radius (Å)	Element	Radius (Å)
C	0.77	As	1.21
B	0.84	Ge	1.22
P	1.1	Sn	1.4
Si	1.17	Sb	1.41

Element	Radius (Å)	Element	Radius (Å)
C	0.77	As	1.21
B	0.84	Ge	1.22
P	1.1	Sn	1.4
Si	1.17	Sb	1.41

For elements with covalent radii greater than 1.17Å, strain will be biaxially compressive. For covalent radii less than 1.17Ǻ, strain will be biaxially tensile.

Concentration of donor and acceptor atoms on lattice sites equals carrier concentration.

Implant and Anneal Conditions

Implant Techniques

- Ion Implantation (Beamline)
- Plasma Immersion
- Cluster
- Molecular

Thermal Treatments

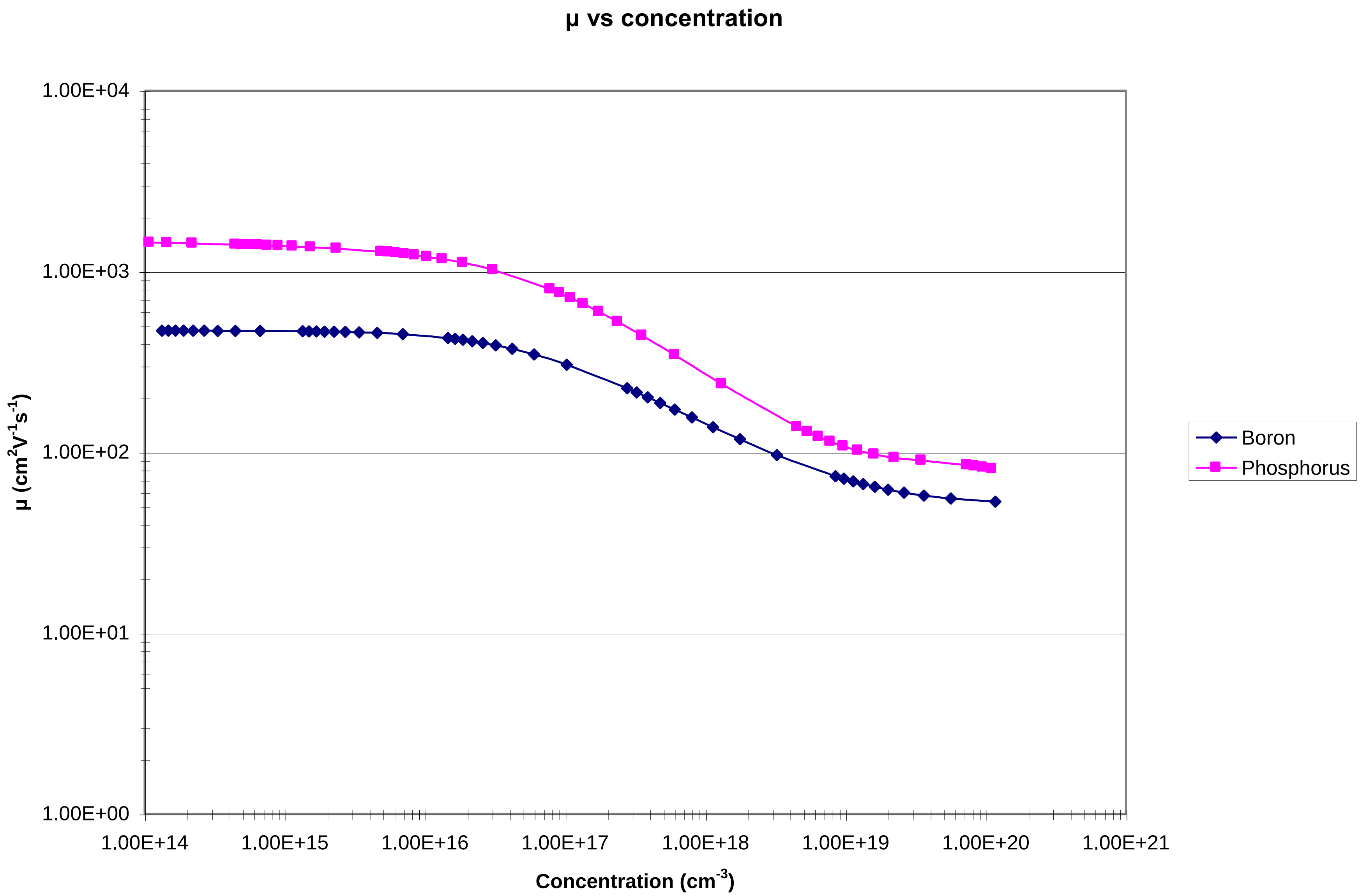
- RTA
- SPER
- LSA (Laser Spike Anneal)
- Flash (Arc-lamp fRTP or Xe-lamp FLA (flash lamp anneal))
- DSA (Dynamic Durface Anneal)
- Combinations

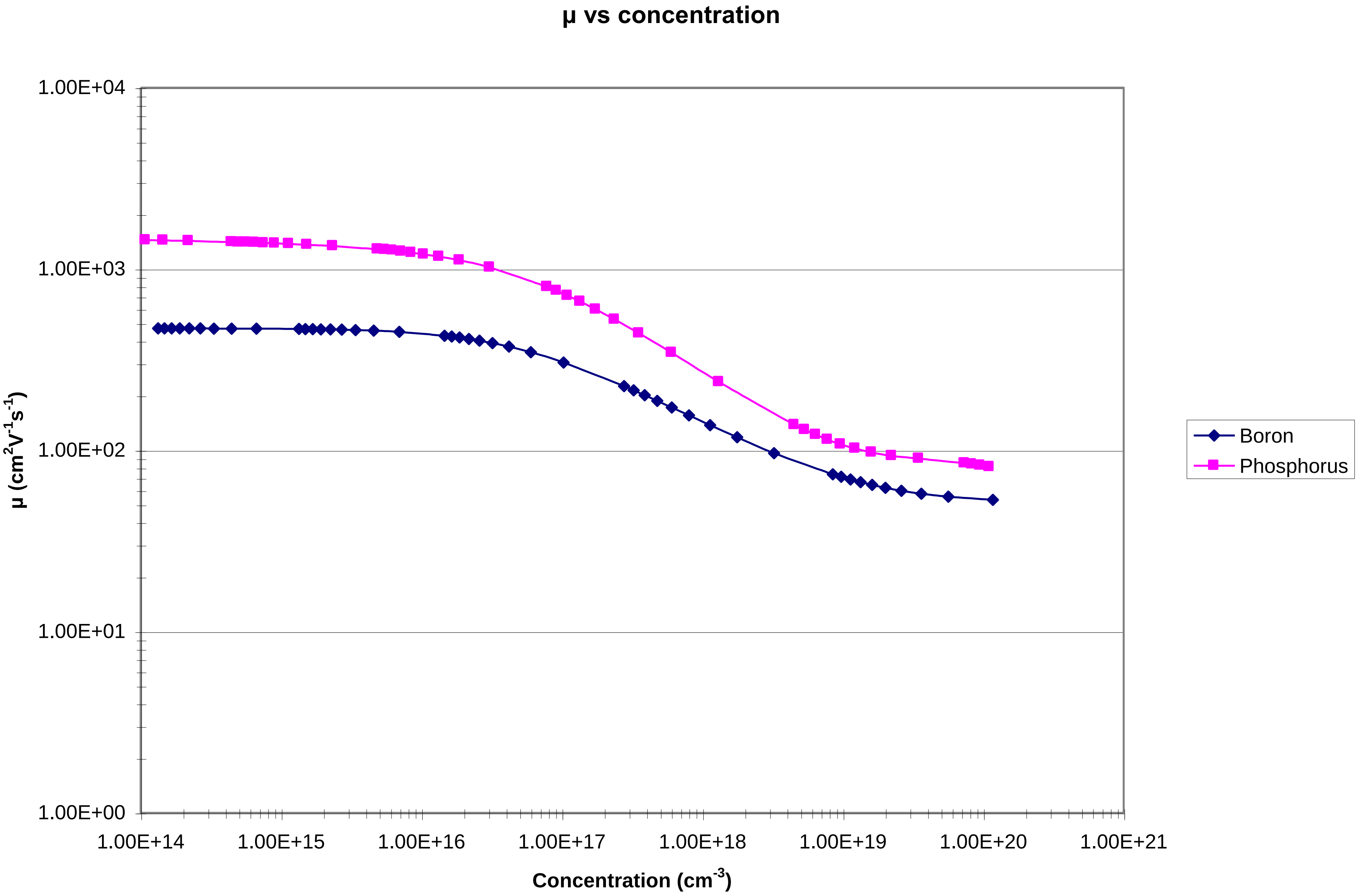
A.S.T.M. Algorithm

1977-1980 U.S. Bureau of Standards

- As grown crystals doped with B and P
- Measured resistivity and dopant concentration
- Relationship for mobility and carrier concentration over the range 1014cm^{-3} to 1020cm^{-3}
- Arsenic exhibits same relationship as P
- Adopted as A.S.T.M. standard F723-99

A.S.T.M. Curve


μ vs concentration
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
μ (cm²V⁻¹s⁻¹)
1.00E+14
1.00E+15
1.00E+16
1.00E+17
1.00E+18
1.00E+19
1.00E+20
1.00E+21
Concentration (cm⁻³)
Boron
Phosphorus


μ vs concentration
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
μ (cm^{2}V^{-1}s^{-1})
1.00E+14
1.00E+15
1.00E+16
1.00E+17
1.00E+18
1.00E+19
1.00E+20
1.00E+21
Concentration (cm^{-3})
Boron
Phosphorus

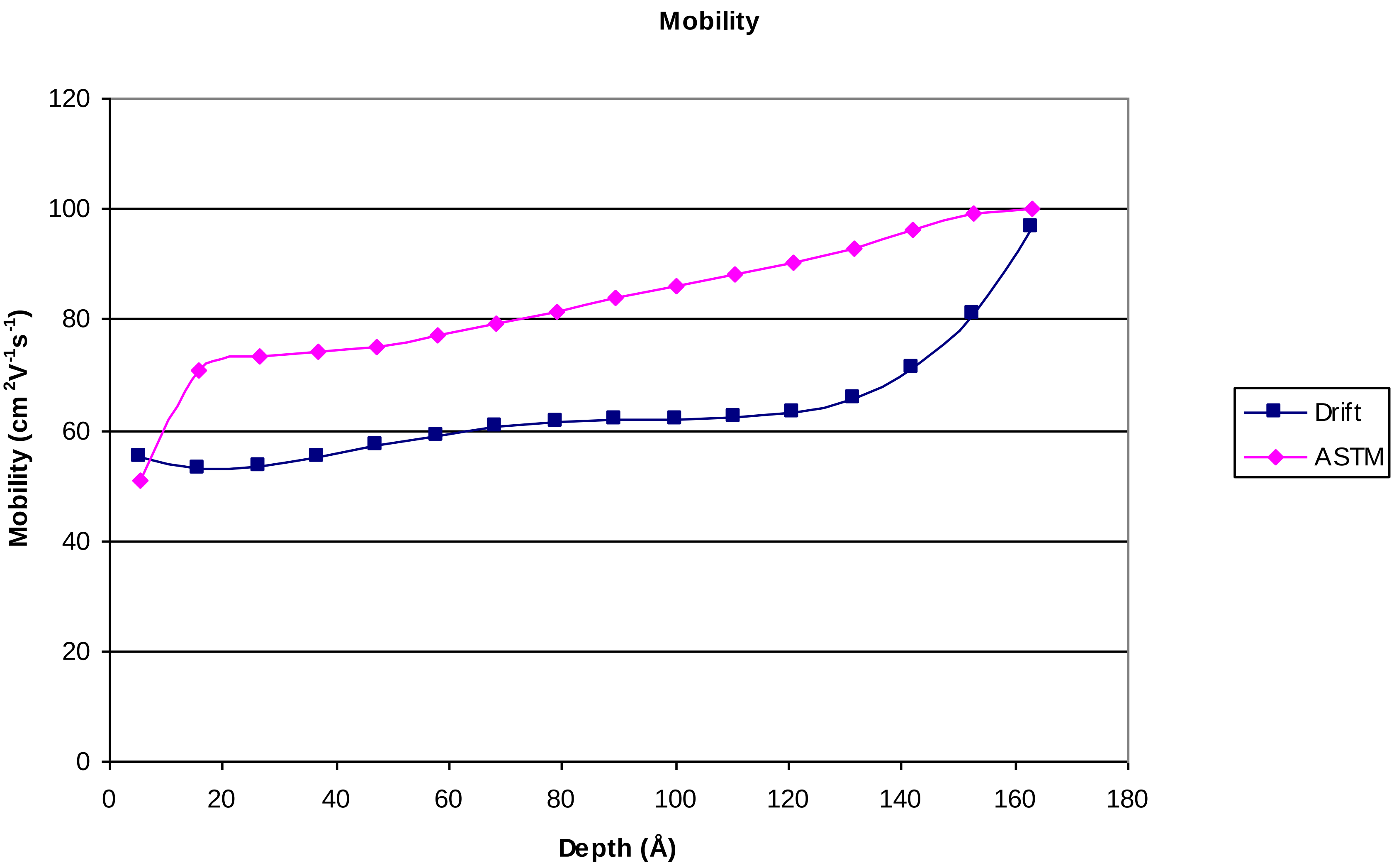
Mathieson's Rule

$$\frac{1}{\mu_o} = \frac{1}{\mu_{phon}} + \frac{1}{\mu_{coul}}$$

μ_o= A.S.T.M. mobility, function of carrier concentration.

μ_{phon}= phononic contribution to mobility, interaction of holes or electrons with lattice vibrations, a function of temperature.

μ_{coul}= Coulombic contribution to mobility, interaction of holes and electrons with charged lattice positions, a function of carrier concentration.


Mobility
Mobility (cm^{2}V^{-1}s^{-1})
0
20
40
60
80
100
120
0
20
40
60
80
100
120
140
160
180
Depth (Å)
Drift
ASTM

Generation of Scatter Defects

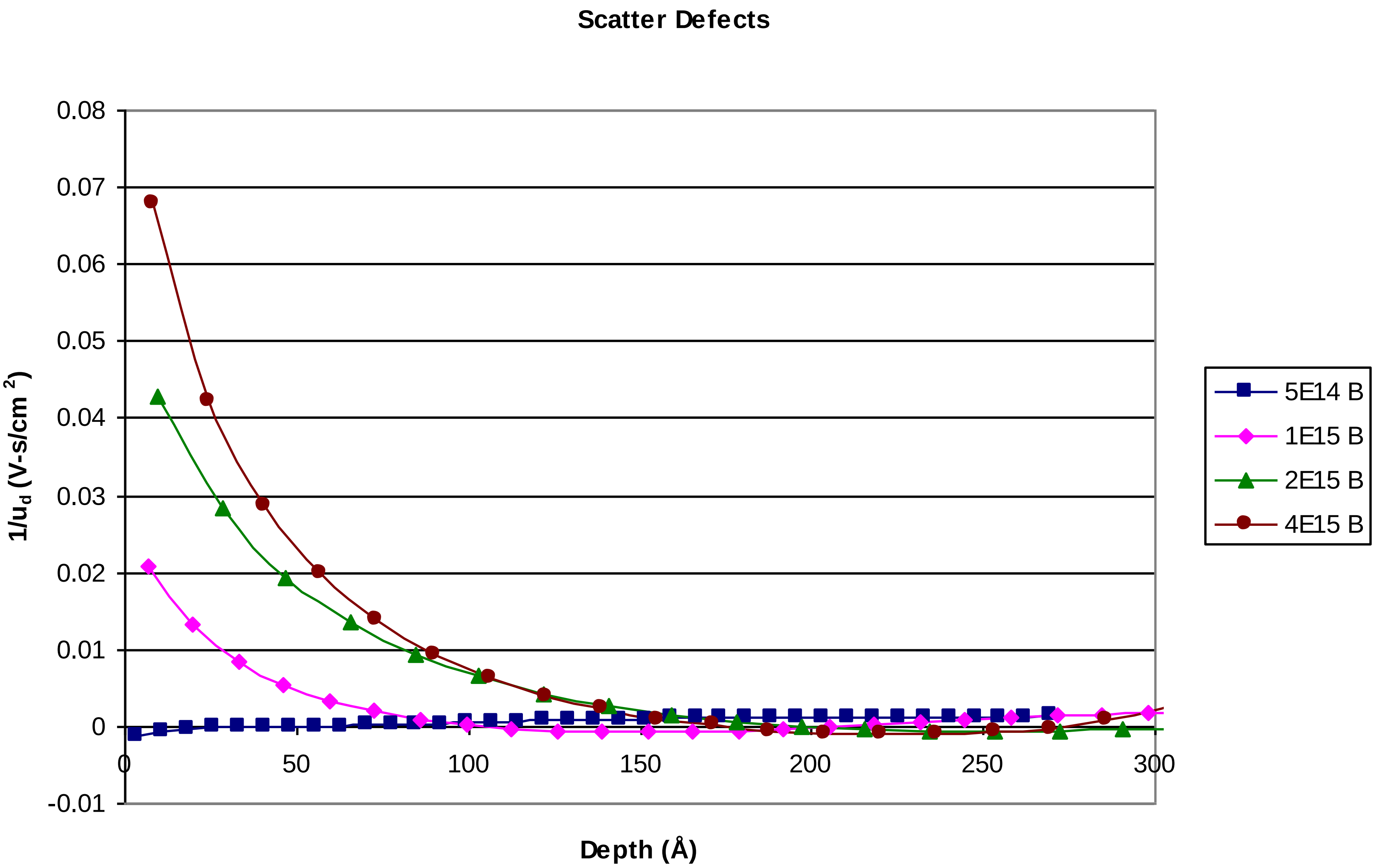
$$\frac{1}{\mu} = \frac{1}{\mu_o} + \frac{1}{\mu_d}$$

$$\frac{1}{\mu_d} = \frac{1}{\mu} - \frac{1}{\mu_o}$$

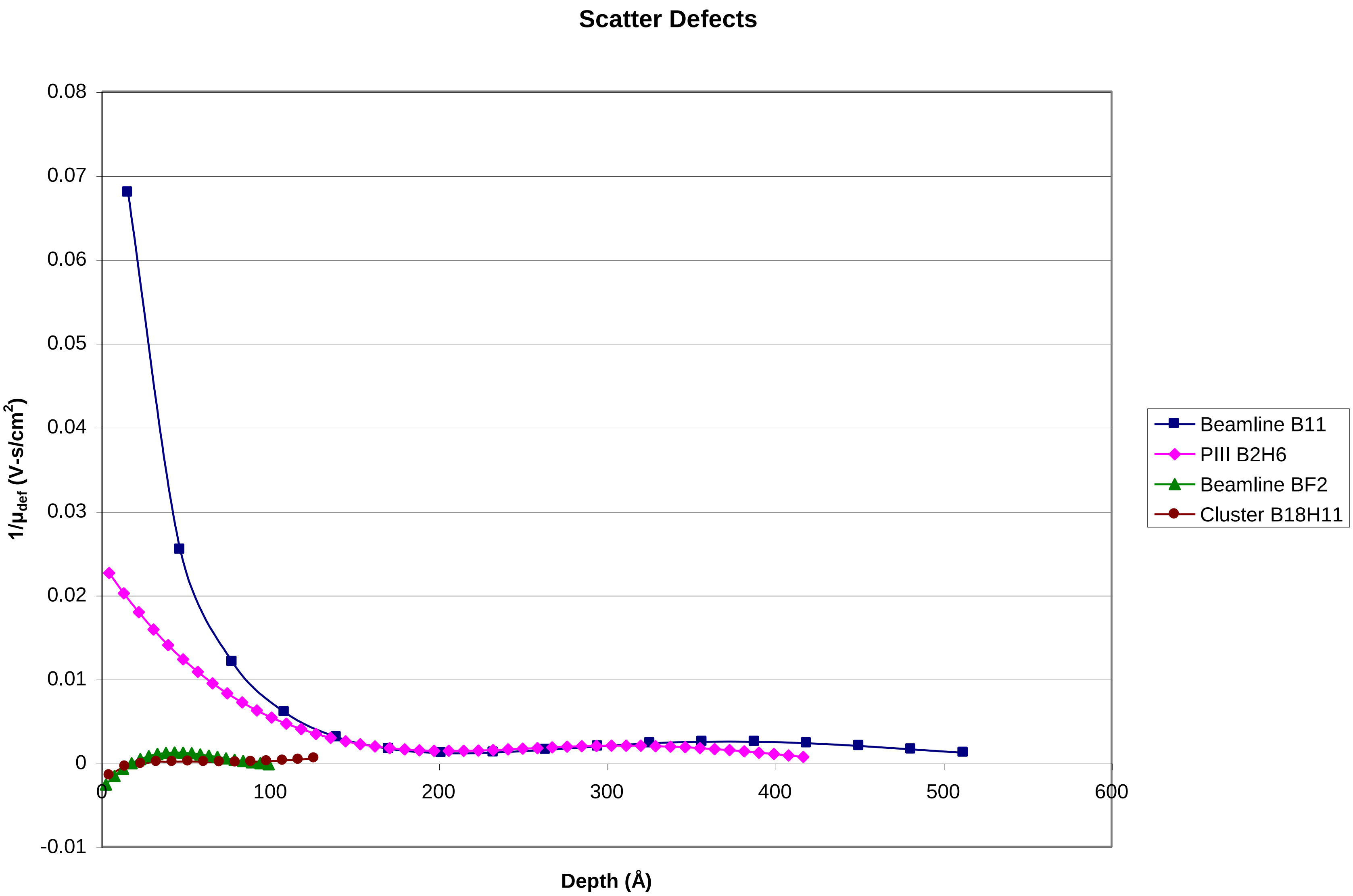
μ_d= contribution of scatter defects

μ= measured mobility by DHE CAOT

μ_o= A.S.T.M. mobility calculated for measured carrier distribution



B Implanted at 1.25keV, 1015°C spike anneal in N_2


Scatter Defects
1/μdef (V-s/cm2)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0
100
200
300
400
500
600
Depth (Å)
Beamline B11
PIII B2H6
Beamline BF2
Cluster B18H11

Generation of Scatter Defects

1. Most specimens indicated significant scatter defect contributions.
2. Occasionally specimens were found with zero scatter defects.

Factors which affected scatter defect contributions:

1. Type of Implant (e.g. BL, PLAD, Cluster)
2. Implant Energy
3. Implant Dose
4. Type of Anneal
5. Anneal Temperature
6. Anneal Time

Introduction of Strain

1. Group IV atoms (e.g. C and Ge)
2. Dopant atoms (e.g. B, P, and As)

$$\frac{1}{\mu_s} = \text{contribution of strain to mobility}$$

$$\frac{1}{\mu} - \frac{1}{\mu_o} = \frac{1}{\mu_d} - \frac{1}{\mu_s}$$

If $\frac{1}{\mu_d}$ were eliminated

$$\frac{1}{\mu} - \frac{1}{\mu_o} = -\frac{1}{\mu_s}$$

Where

μ= measured mobility

μ_o= mobility calculated from measured concentration and A.S.T.M. algorithm

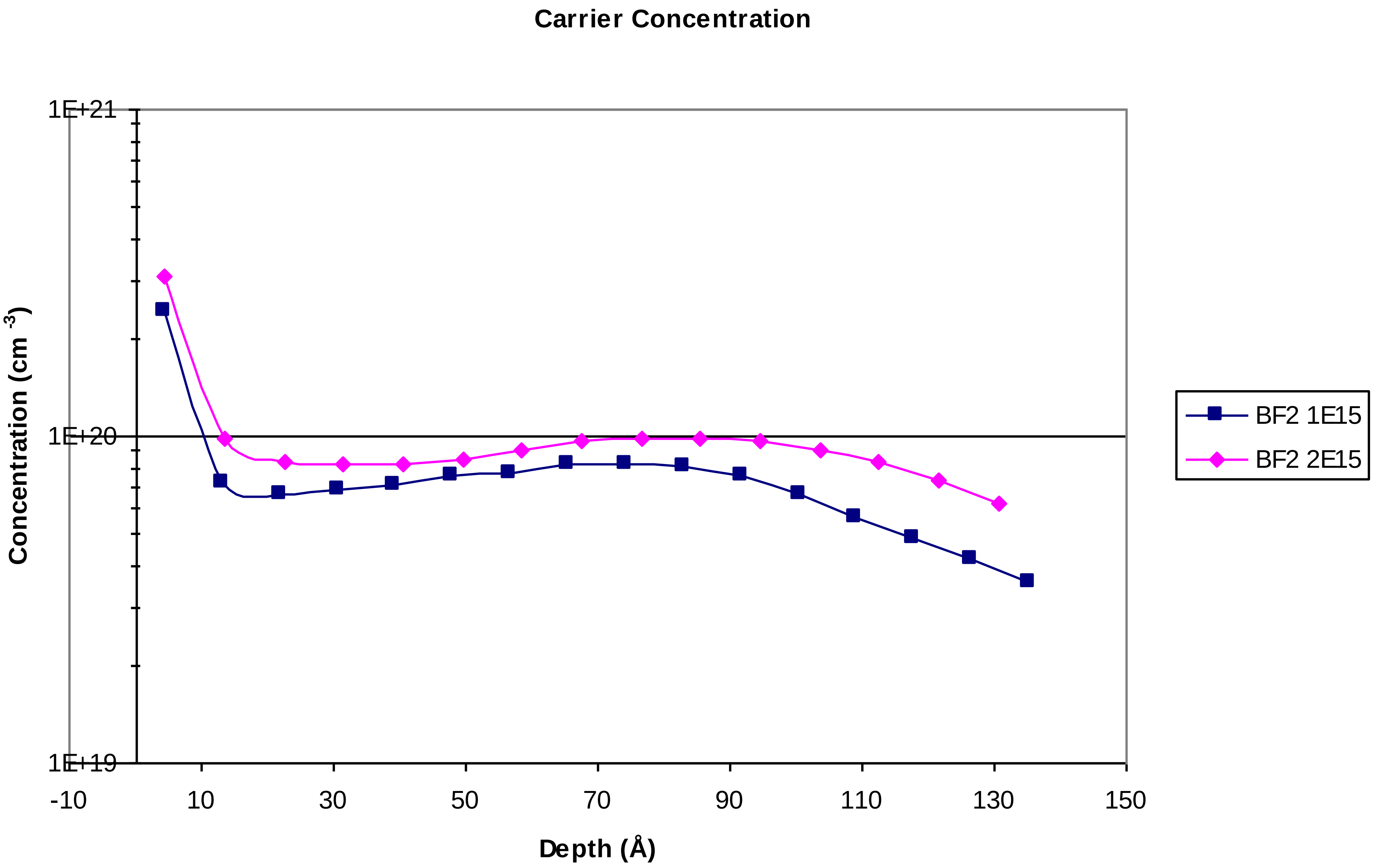
μ_s= mobility strain component

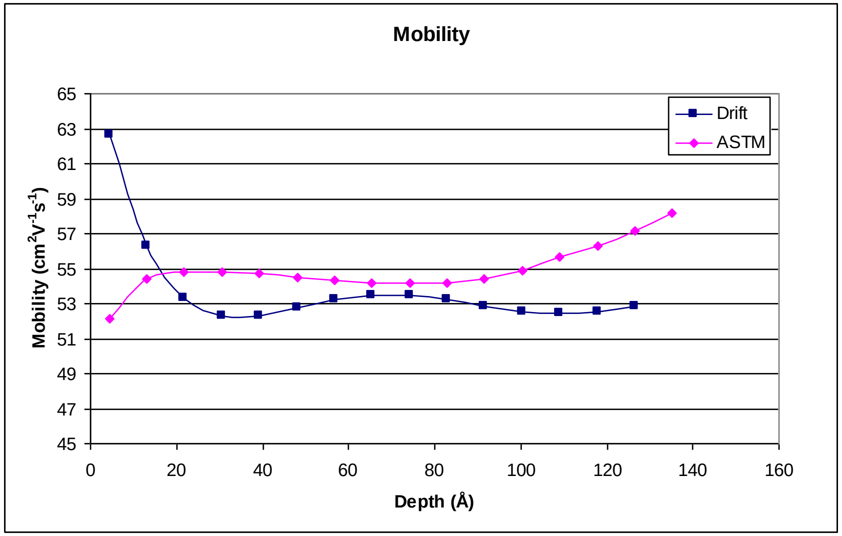
Introduction of Strain

Additional implantation of Group IV elements results in increased scatter defects.

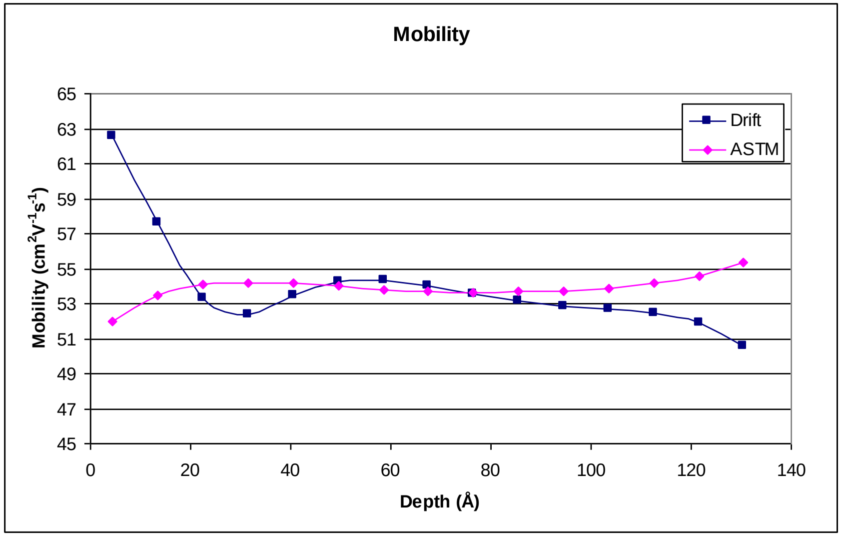
In one study comparing mobilities for As and P implants with and without C implants, specimens without C exhibited little or no scatter defects.

$$\frac{1}{\mu_d} - \frac{1}{\mu_s} = \frac{1}{\mu} - \frac{1}{\mu_o}$$

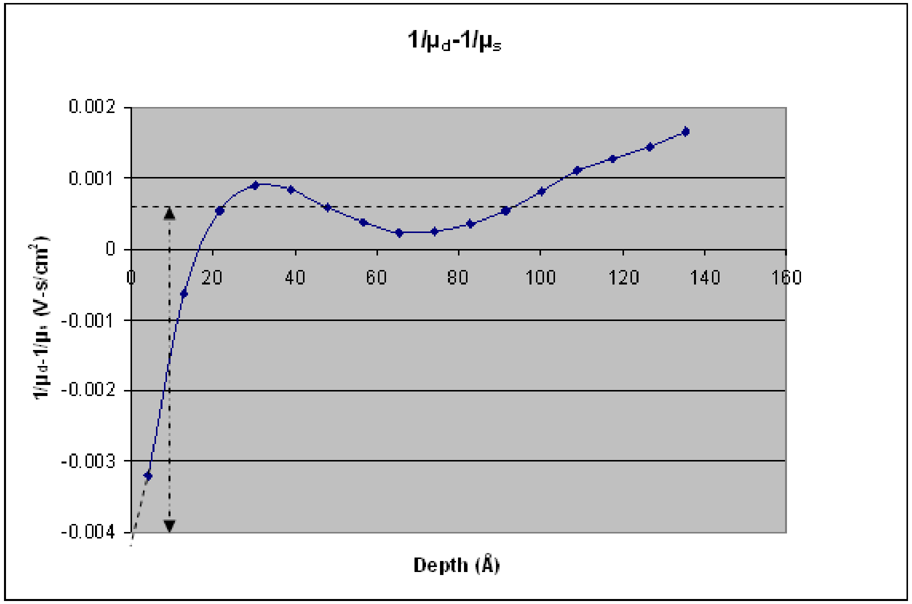

Carrier Concentration
Concentration (cm -3)
1E+21
1E+20
1E+19
-10
10
30
50
70
90
110
130
150
Depth (Å)
BF2 1E15
BF2 2E15



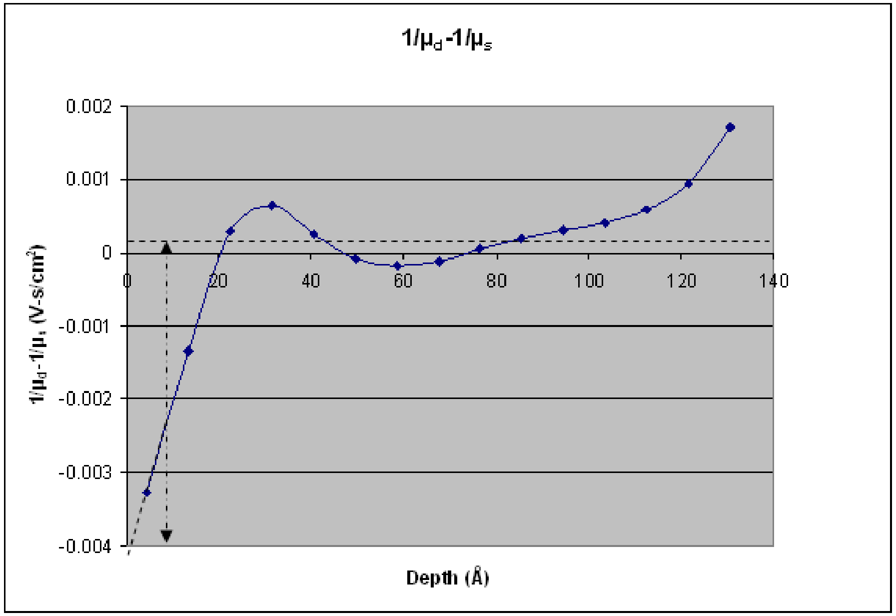
1E15 BF2 @ 337eV, spike RTA 1050°C



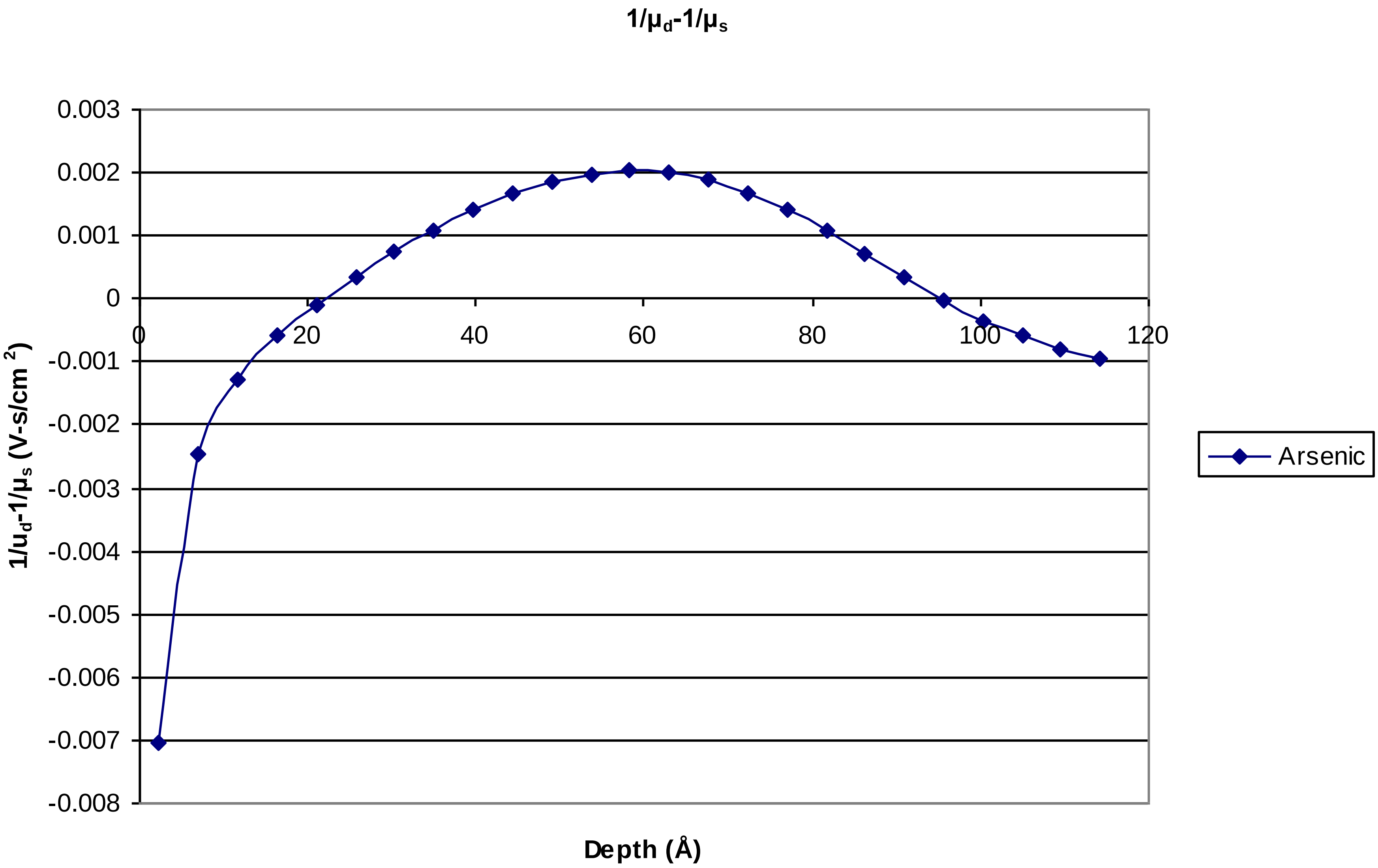
2E15 BF2 @ 337eV, spike RTA 1050°C

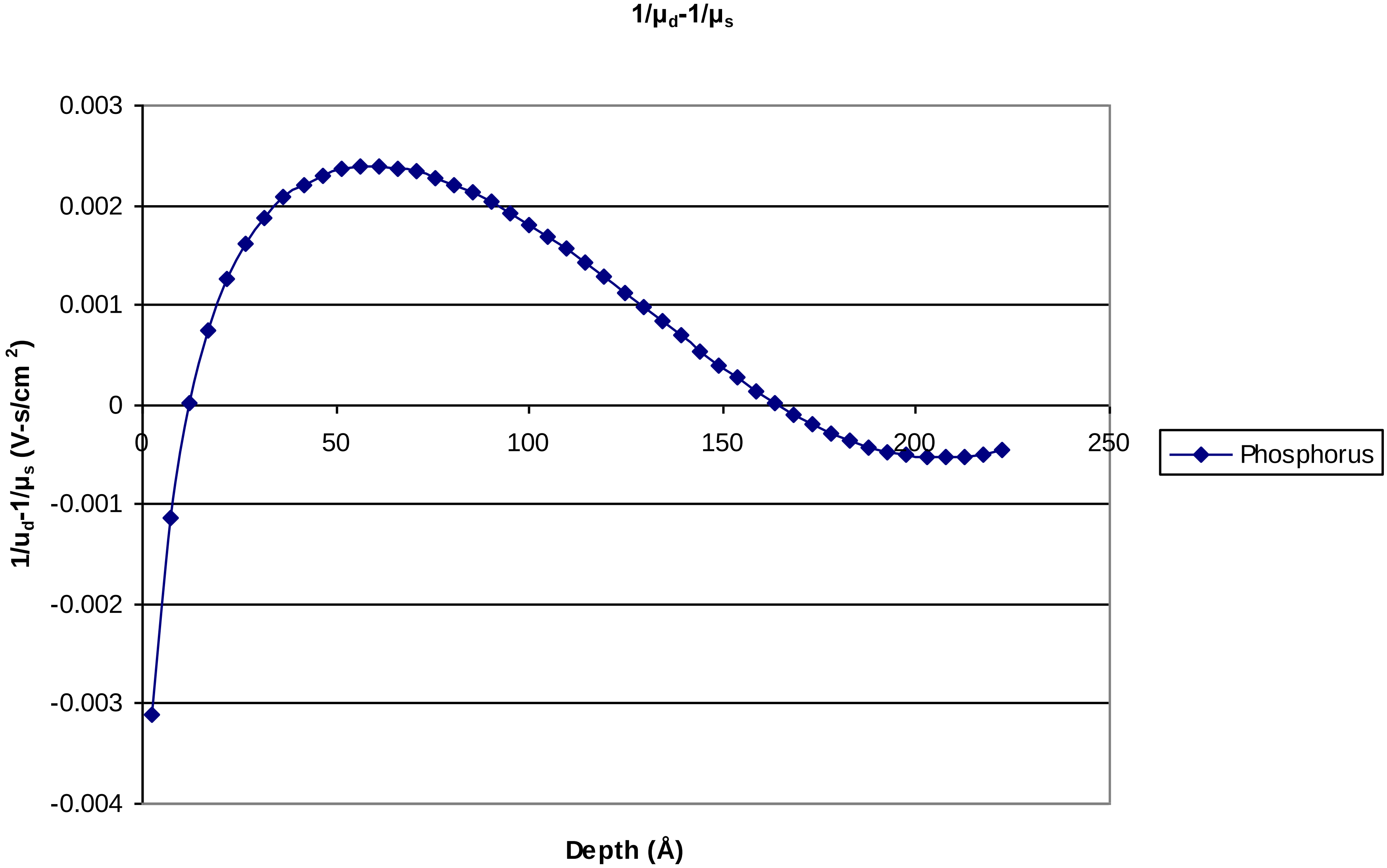


1E15 BF2 @ 337eV, spike RTA 1050°C

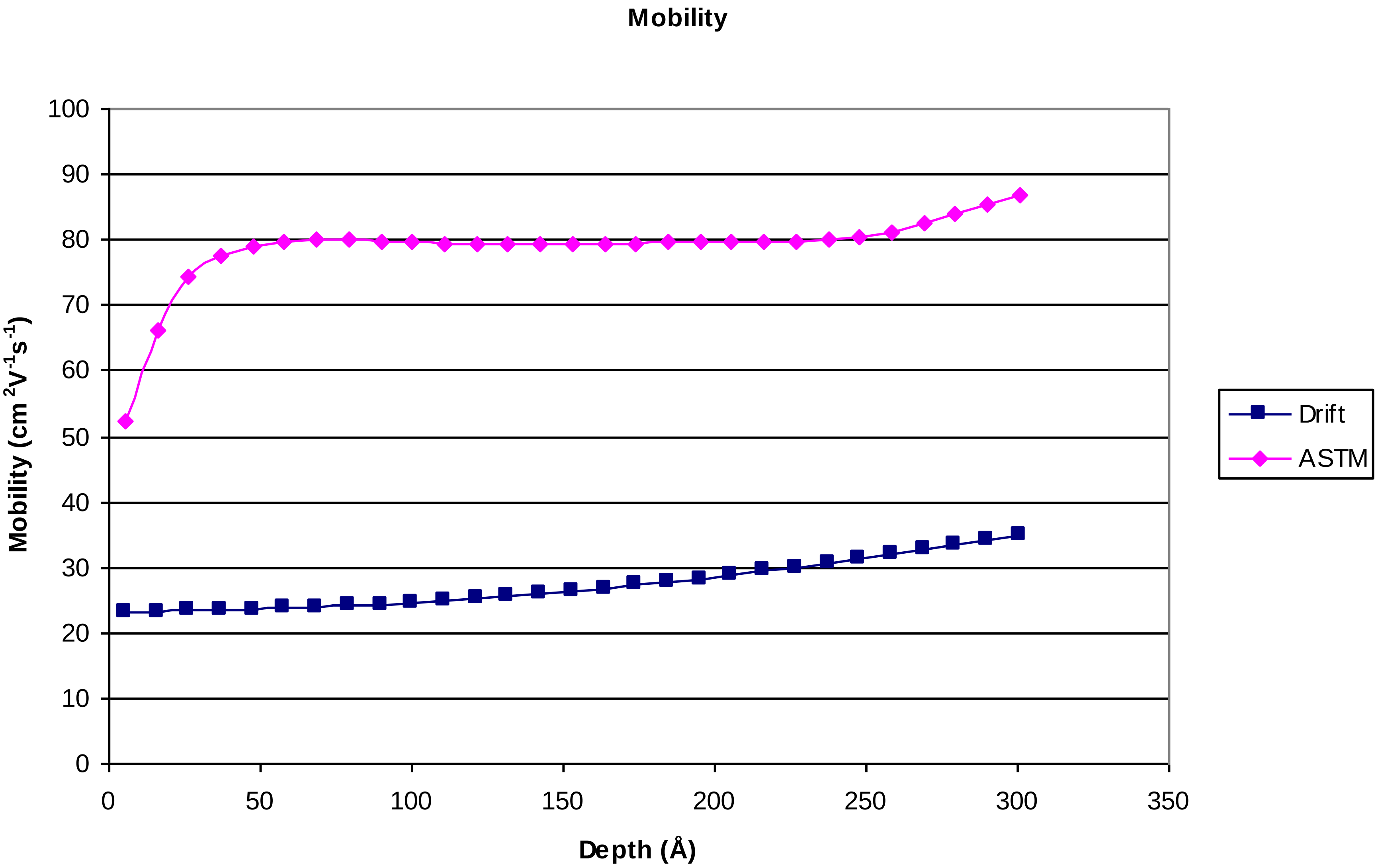


2E15 BF2 @ 337eV, spike RTA 1050°C


$1/\mu_d-1/\mu_s$
$1/u_d-1/\mu_s$ (V-s/cm ^{2})
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
0
20
40
60
80
100
120
Depth (Å)
Arsenic



$1/\mu_d$-$1/\mu_s$
$1/u_d$-$1/\mu_s$ (V-s/cm ^{2})
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
0
50
100
150
200
250
Depth (Å)
Phosphorus



As implant followed by C implant

Conclusions

1. Implant processes should be matched with anneal processes which eliminate scatter defects.
2. Tensile as well as compressive strain improve mobility of electrons.
3. Tensile strain improves mobility of holes.