

EE 221 Device Physics

Diffusion and Oxidation

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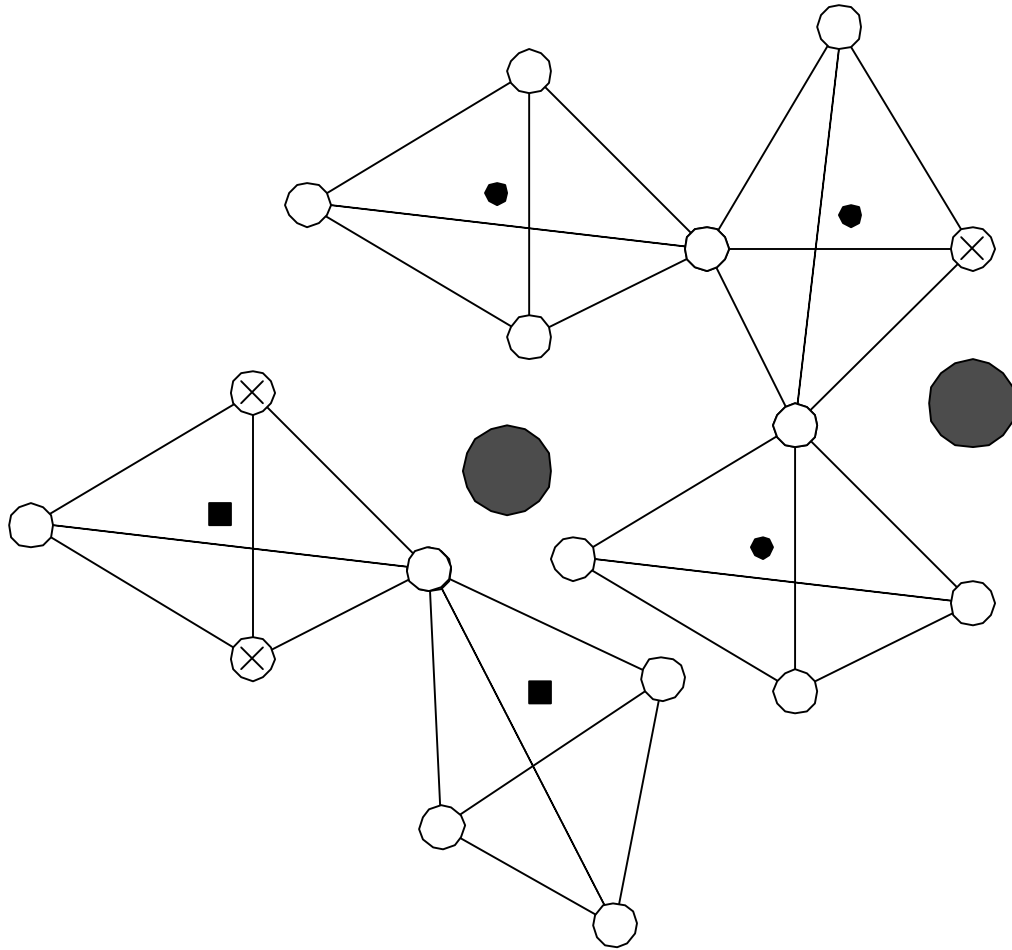
Silicon dioxide

- What is SiO_2 ?
- What is SiO_2 used for?
- Advantages and Disadvantages of SiO_2
- How is it grown?
 - Dry
 - Wet
- Numerical Examples

What is SiO₂?

- Two forms
 - Single crystal (quartz)
 - Amorphous
- We are interested in Amorphous SiO₂
 - Random three dimensional network of SiO₂ constructed from polyhedra of oxygen ions.
 - This material is more porous than Quartz (density of 2.15-2.25g/cm³ compared to 2.65 25g/cm³)

What is SiO_2 ?



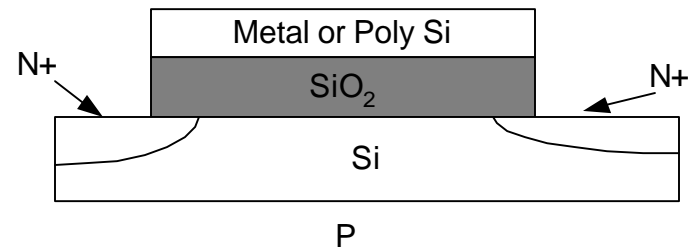
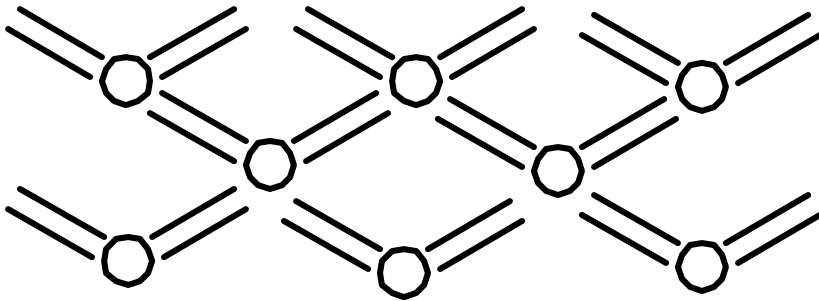
- Network modifier
- ⊗ Nonbridging oxygen
- Silicon
- Network former
- Bridging oxygen

The O-Si-O Bond angle is 109°

Tetrahedral distance between Si and O ions is 1.6\AA

What is SiO_2 used for?

- MOS Metal Oxide Semiconductor
- Device passivation
 - Combines with dangling bonds to reduce surface states

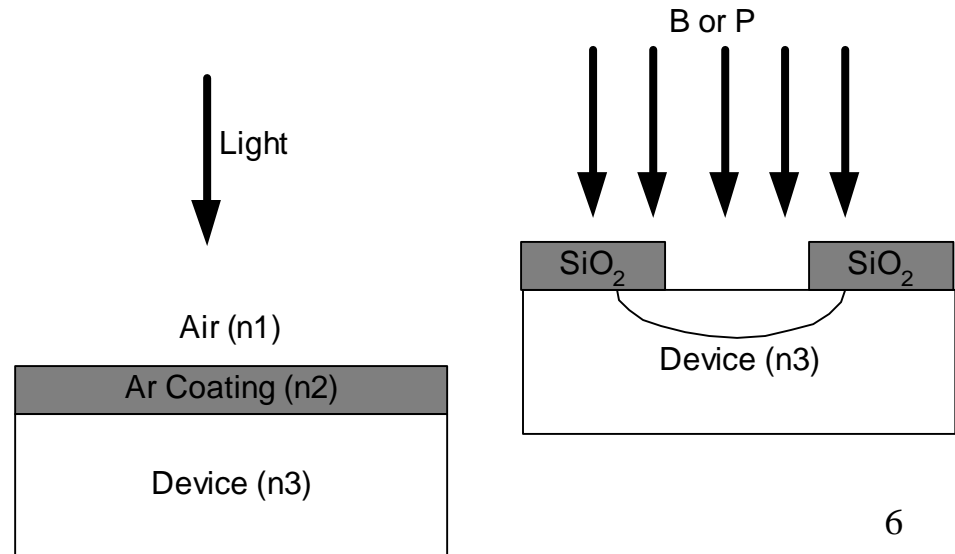


What is SiO₂ used for?

- Diffusion Masks
 - Block the diffusion of B and P for example
- Antireflective coating for Photodevices

$$n_2 = \sqrt{n_1 n_3},$$

$$\text{thickness} = \frac{l}{4n_2}$$



Advantages and Disadvantages of SiO_2

- CMOS digital logic gates use little power when not switching logic state, thus high levels of integration are possible because the standby power consumption is low.
- SiO_2 is a native film that is quite easy to grow. All that is required is heat and oxygen or steam.

Advantages and Disadvantages of SiO_2

- SiO_2 consumes Si while growing. 44% of the SiO_2 layer comes from the original Si.
 - This leads to a non-planer structure after each oxidation step.
- Due to the large increase in volume there is $2\text{-}4 \times 10^9$ dyn cm^{-1} of compressive strain.
 - This causes dislocations.
- Oxidation-Induced Stacking Faults (these can be removed by a high temp treatment.

Advantages and Disadvantages of SiO_2

- The large dielectric constant leads to larger capacitance values for a given thickness (compared to silicon nitride).

How is it grown?

- The oxidizing species must diffuse through the SiO₂ layer that has already grown. This leads to a linear regime of growth and a parabolic regime of growth. Given by the equation:

$$X^2 + A(\mathbf{mm})X = B(\mathbf{mm}^2 / \mathbf{hr})t(\mathbf{hr})$$

How is it grown?

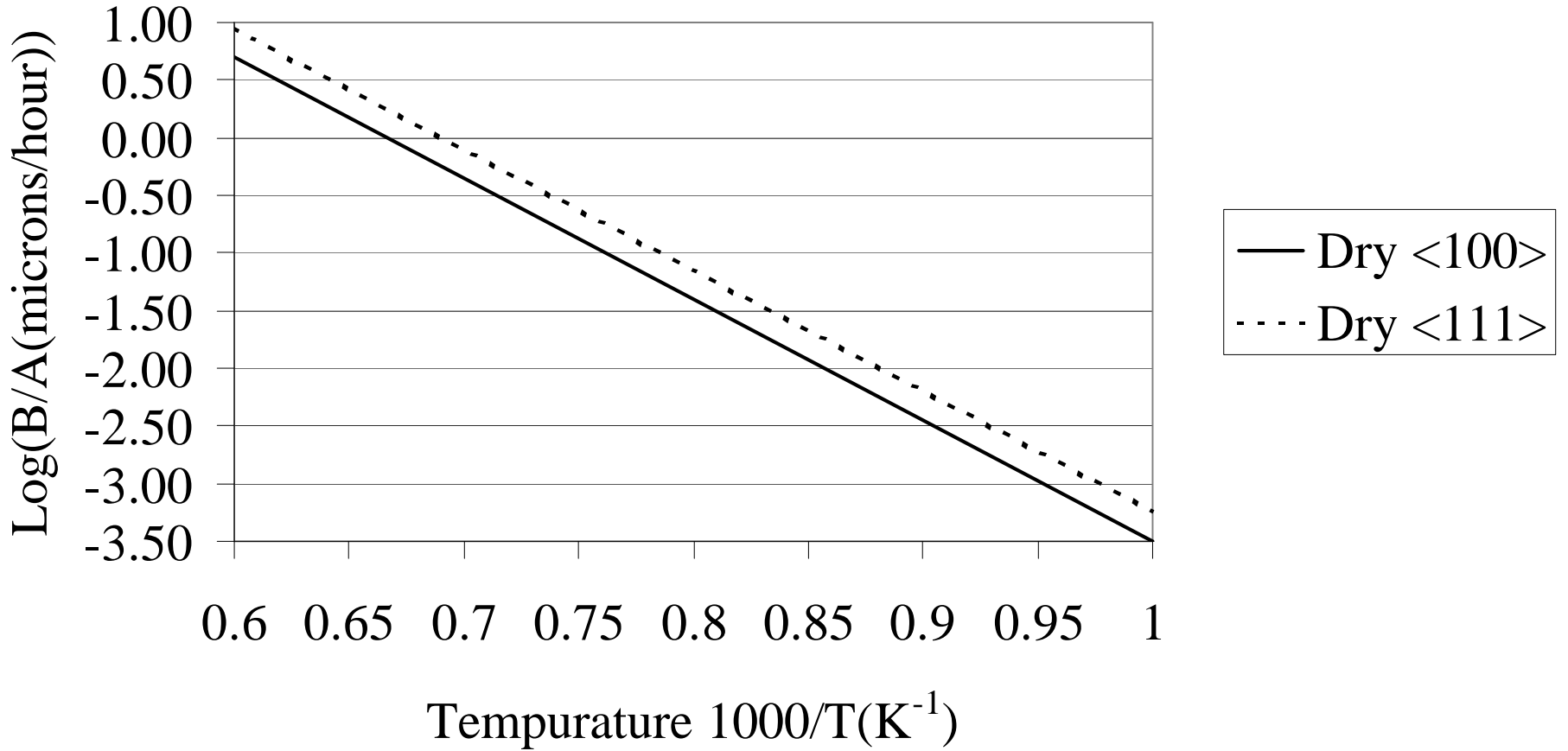
- Dry oxidation: Flow dry O₂ over sample at elevated temperatures.



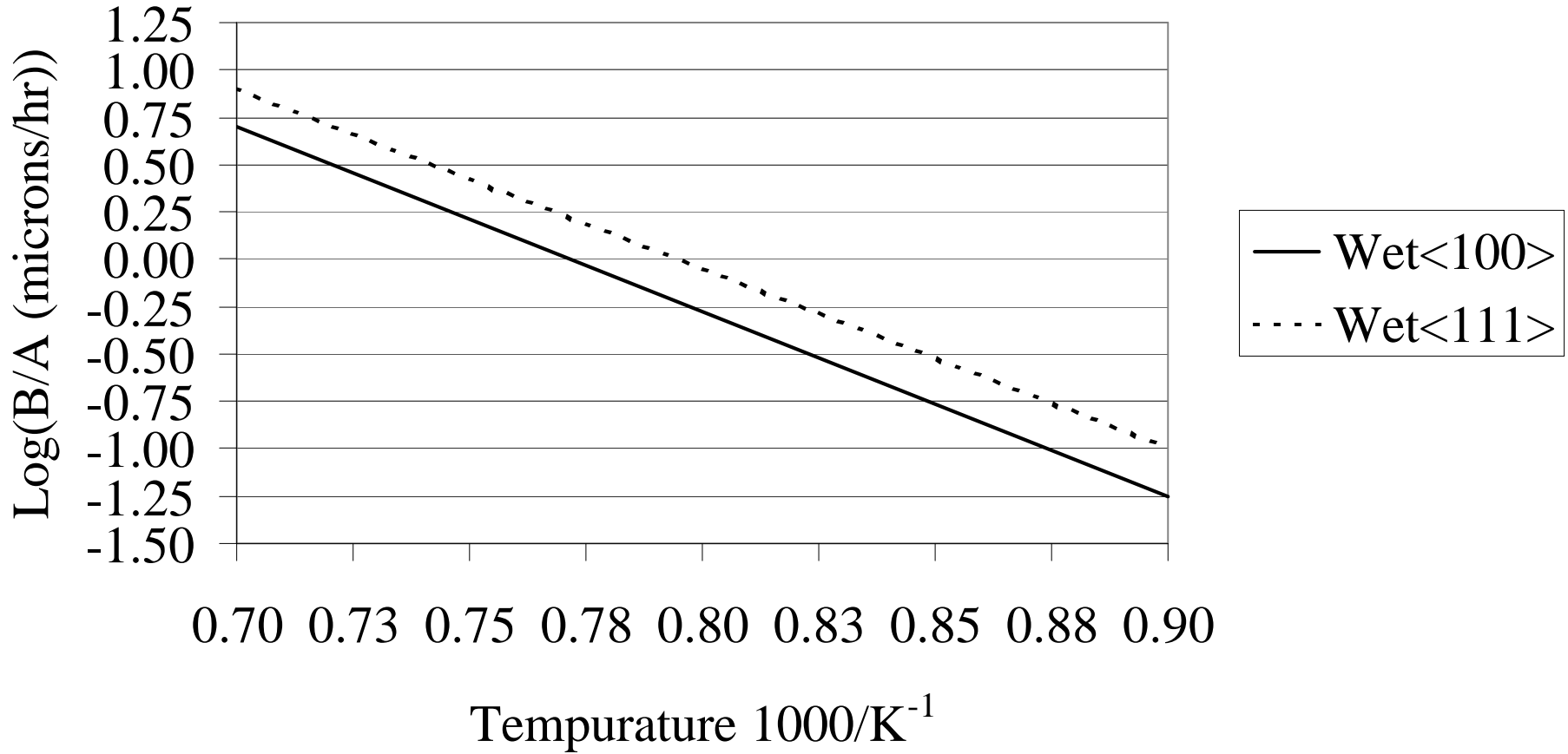
- Wet oxidation: Bubble N₂ through a water bubbler @95C° over sample at elevated temperatures.



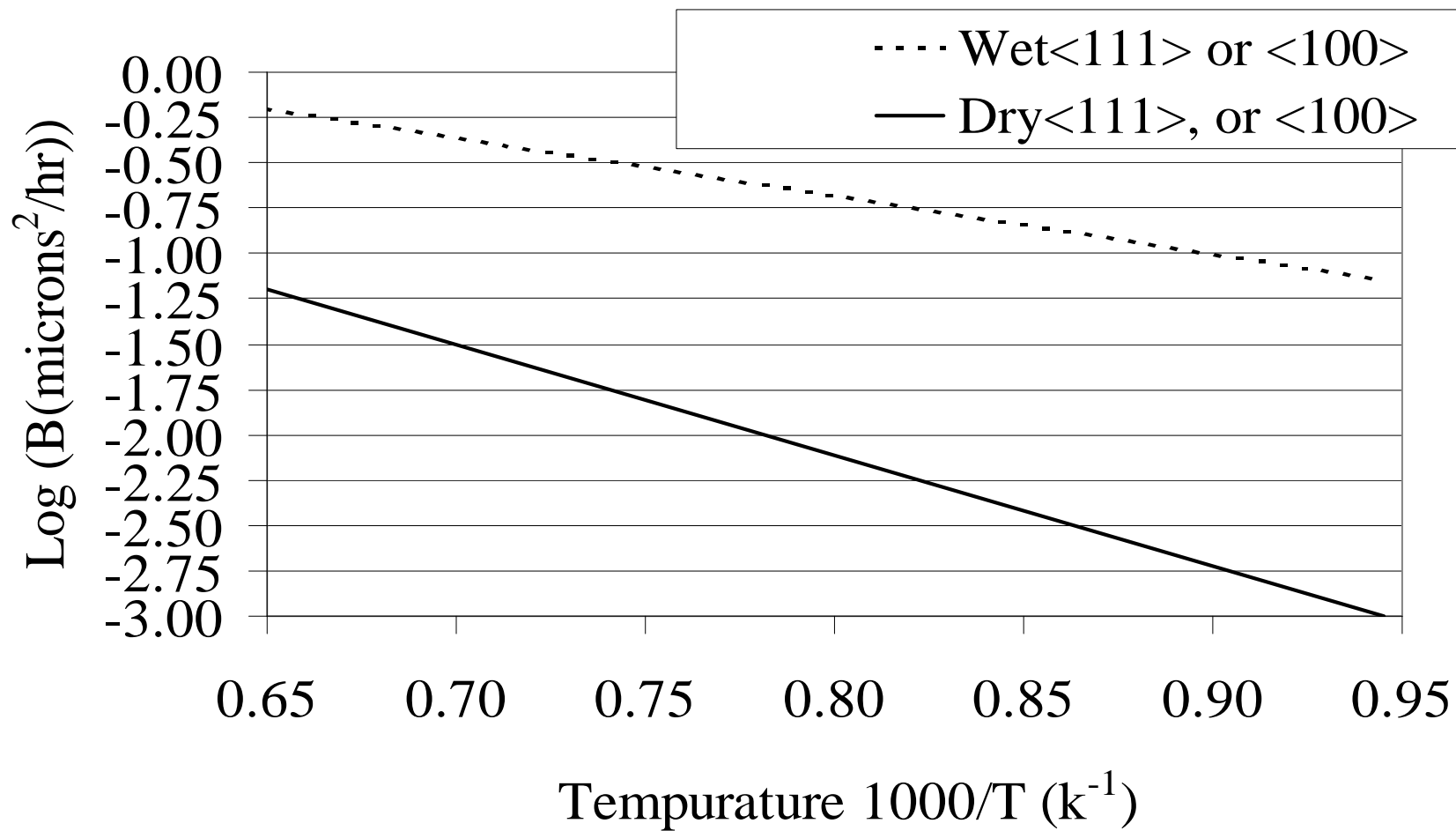
Linear Rate Constant versus Temperature



Wet Oxidation



Parabolic Rate Constant versus Temperature



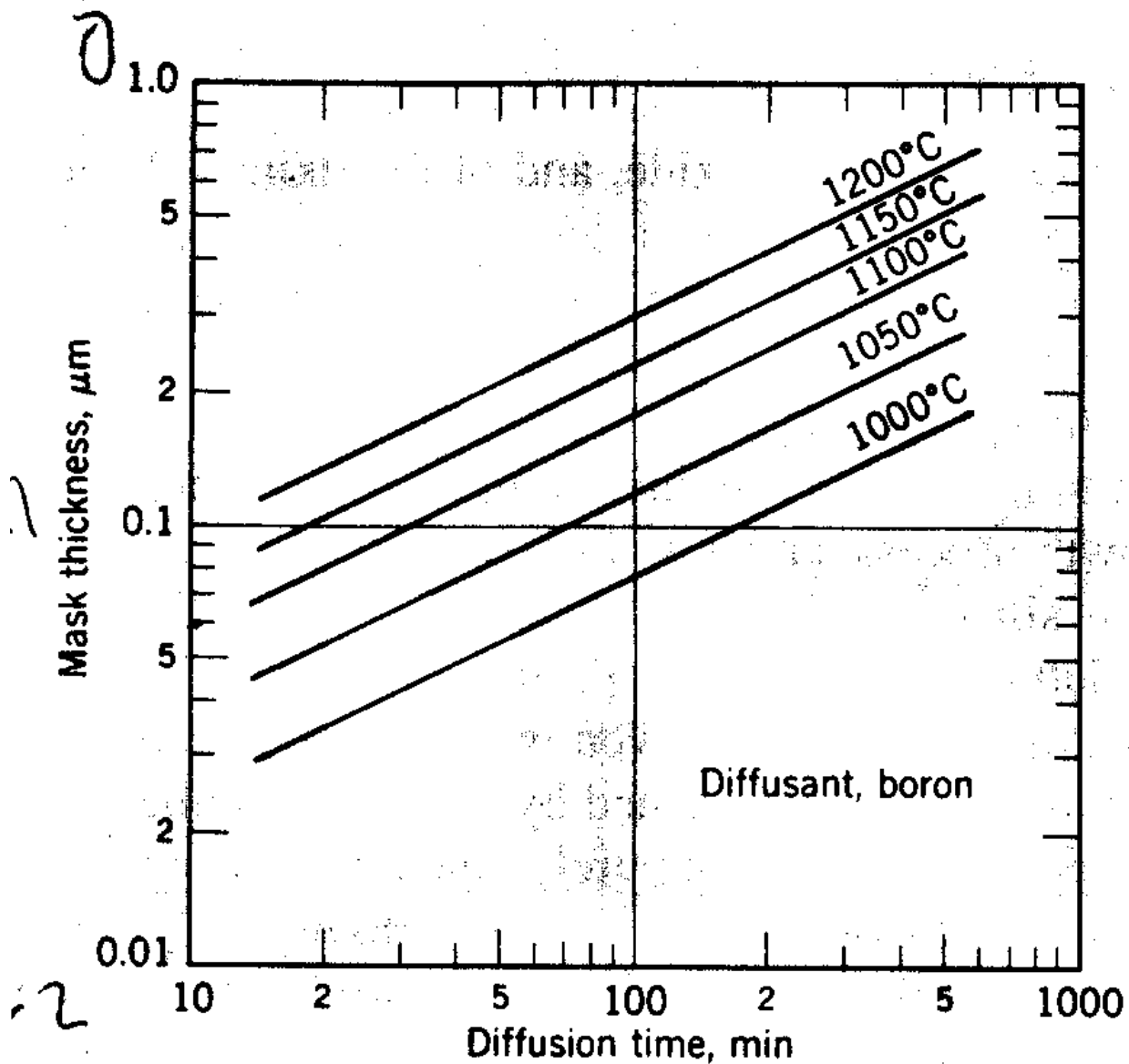


Fig. 7.13 Mask thickness for boron.

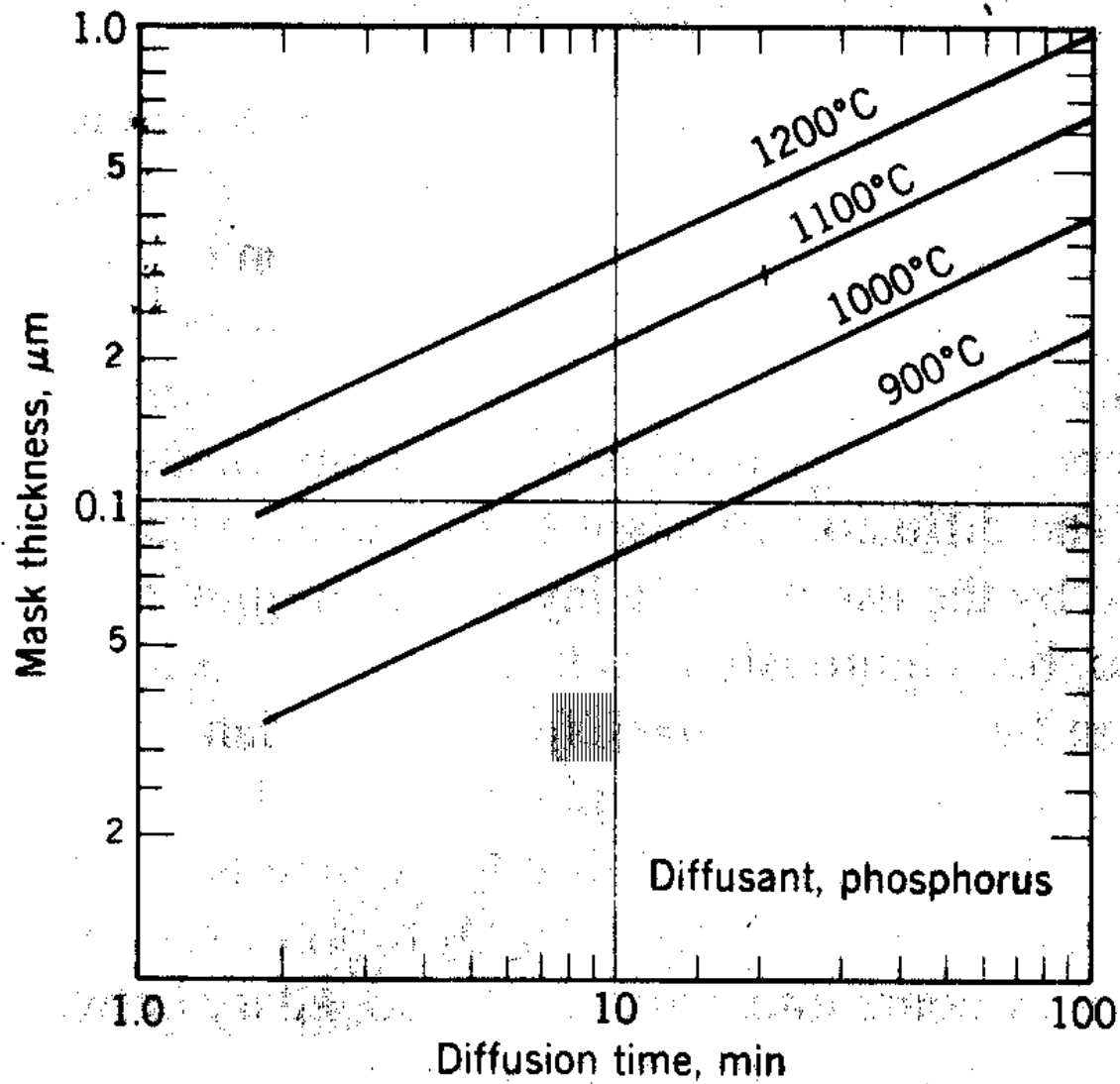


Fig. 7.14 Mask thickness for phosphorus.

Numerical Examples

- How long do we need to grow SiO_2 at 1155°C using a wet process $\langle 111 \rangle$ to protect against a 30 minute 1100°C P diffusion?
- How long do we need to grow SiO_2 at 1265°C using a dry process $\langle 100 \rangle$ to create a MOS insulator capacitance ($C_i = \epsilon_i/d$) of 69nF ?
 - Note: For SiO_2 $\epsilon_i = 3.9 * 8.85e-14\text{F/cm}$

Impurity Diffusion

- Diffusion: An old concept whose mathematics have been worked out for a long time.
- Diffusion: A concentration gradient will cause a force to redistribute particles until there is no concentration gradient.
- Uses: Drain and Source regions for MOS, active regions for BJTs

Impurity Diffusion

- It is ideal for batch processes.
- It does not induce crystal damage
- Diffusion is very useful for p and n type doping in Si.
- Diffusion in III-V(GaAs, InP) is limited to Zn diffusions for p+ layers for ohmic contacts.

Impurity Diffusion

- Diffusion does not give you as exact control over doping concentration and junction depth as does ion-implantation, but it is an inexpensive process.
- Ion-implantation can place oxygen ions under the surface of Si which can be turned into SiO₂.
- Ion-implantation can place a buried layer of dopant atoms in silicon.

Impurity Diffusion (How does it work?)

- At elevated temperatures impurity atoms move around the lattice in a random series of jumps.
 - Three dimensional in nature
 - Only net movement if there is a concentration gradient.

Impurity Diffusion (How does it work?)

- Random series of jumps?
 - Interstitial Diffusion: Impurity atoms jump between the empty spaces in the semiconductor lattice. This is a fast process that Na^+ and Li^+ use to move around the lattice (Bad).
 - Substitutional Diffusion: Impurity atoms jump from one vacant lattice site to an adjacent lattice site. There are not many of these vacant sites so this type of diffusion is slow.

Dopants used for Si diffusion

- Arsenic
 - Low misfit factor which leads to high n-type concentrations. Also has an abrupt doping profile.
- Phosphorus
 - Most common diffusion dopant source. It does not make as abrupt junctions as arsenic.

Dopants used for Si diffusion

- Boron
 - Used for p and p+ diffusions
- Aluminum
 - Annealed into Si to make p+/p(boron) ohmic contacts.

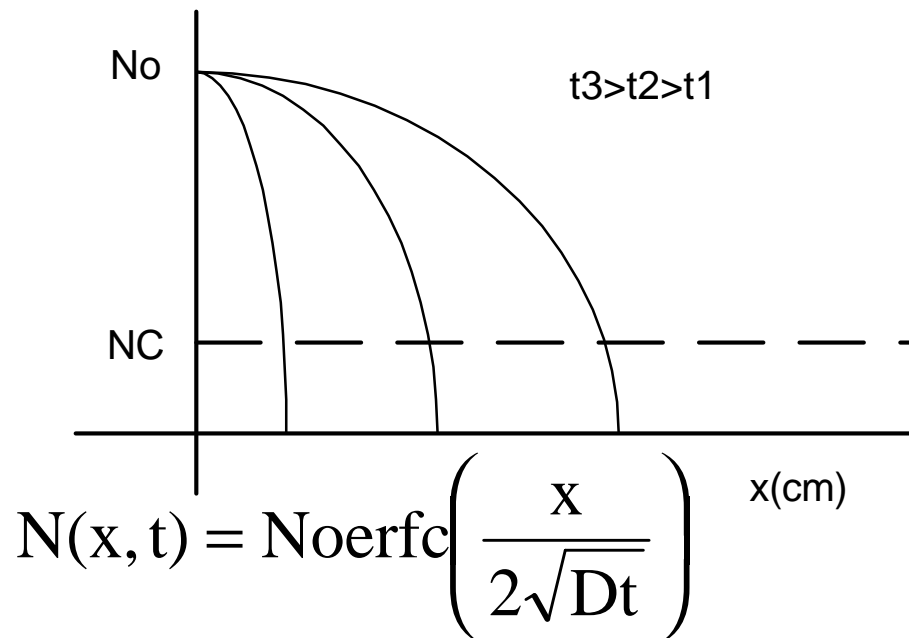
Lateral diffusion

- At the beginning of the diffusion process, there is no concentration gradient in the Si.
- As soon as there are impurity atoms in the Si, there is an impurity gradient in all directions thus diffusion occurs in all directions.
- This causes impurities to diffuse underneath the mask. (not so the ion-implantation)

Types of Diffusion

- “Infinite Source” or Pre-deposition

Doping concentration

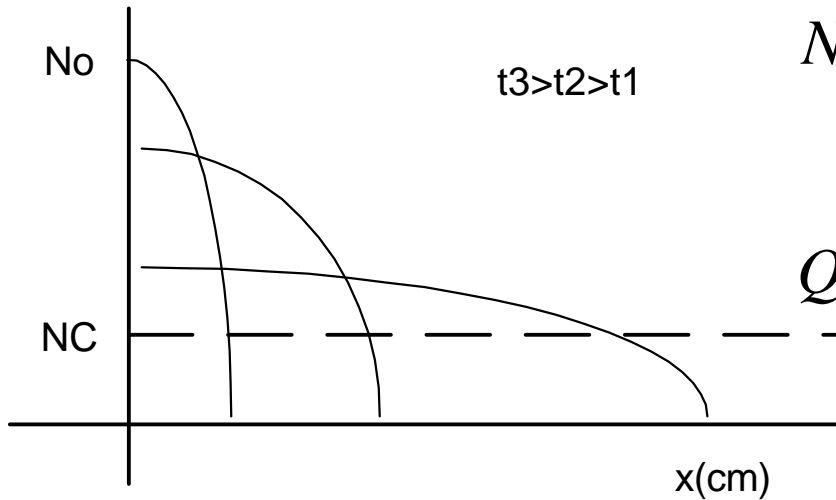


$N_0(\text{cm}^{-3}), D(\text{cm}^2/\text{s}), x(\text{cm}), t(\text{s})$

Types of Diffusion

- “Limited Source” or Drive-in

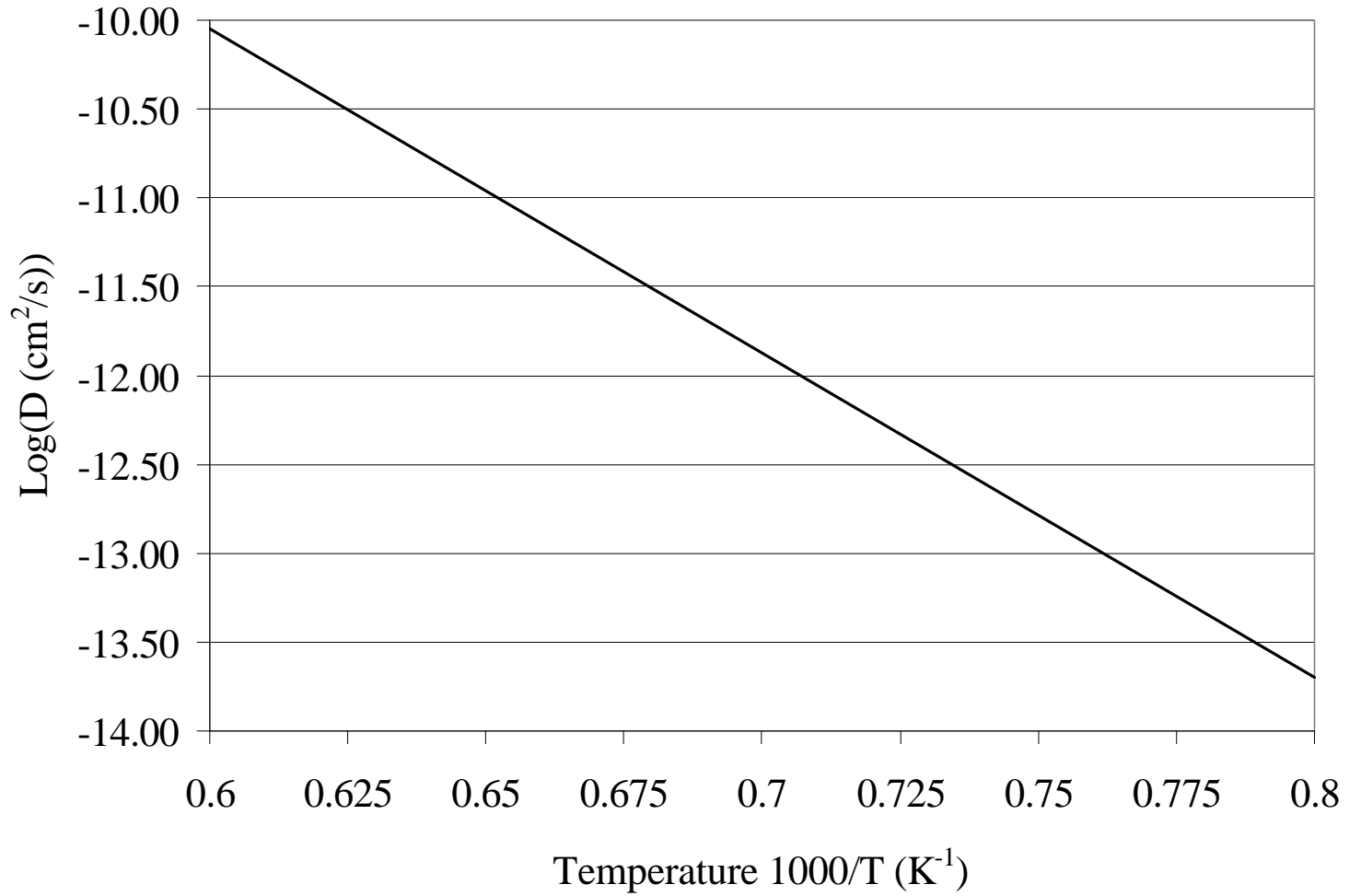
Doping concentration



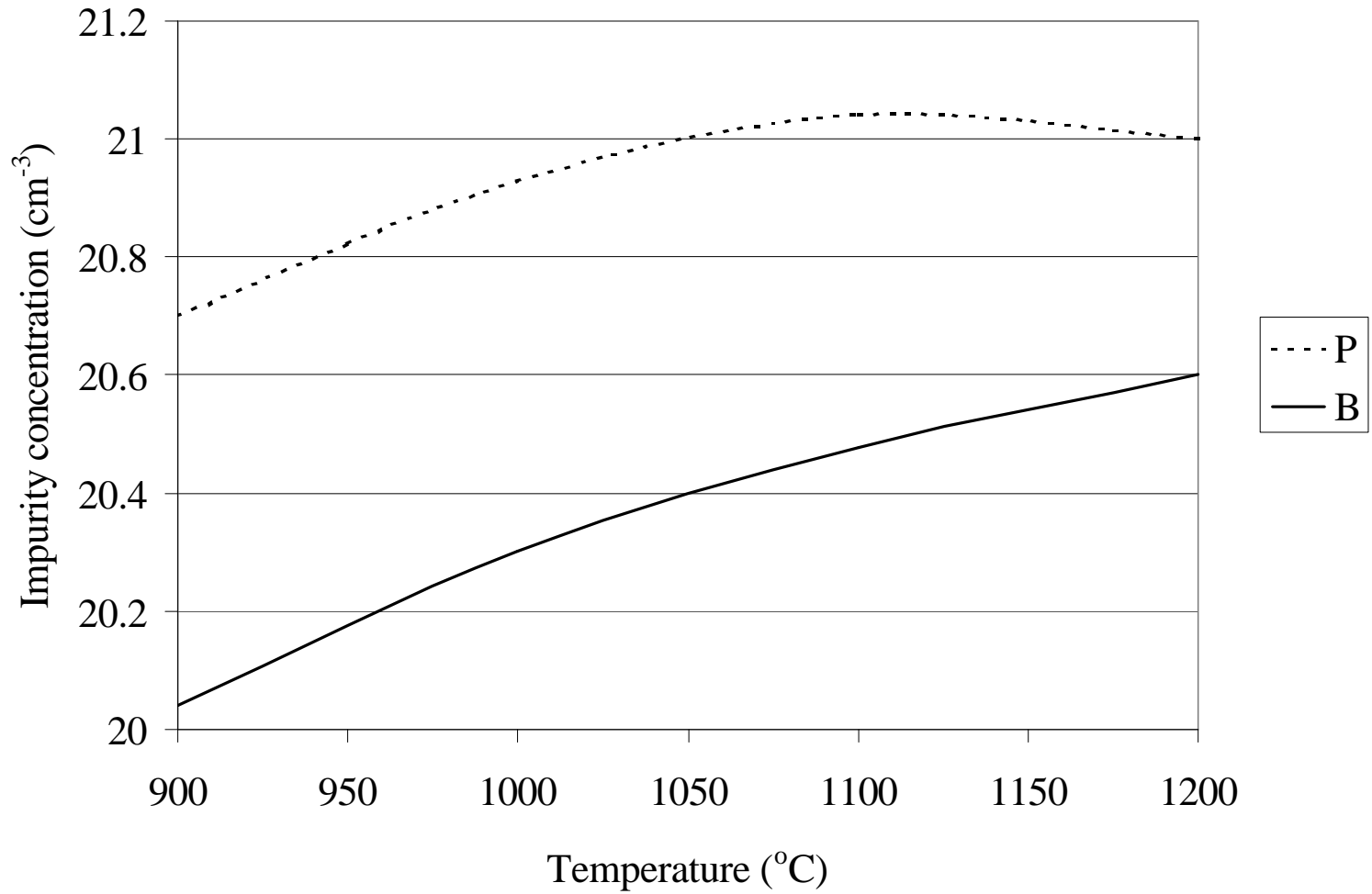
$$N(x, t) = \frac{Q_0}{\sqrt{\pi Dt}} e^{-\left(\frac{x}{2\sqrt{Dt}}\right)^2}$$

$$Q_0 = 2N_{o1} \left(\frac{D_1 t_1}{\sqrt{\pi}} \right)^{\frac{1}{2}}$$

Average Diffusivities for P and B



Solubility limits of B and P



Z	erf(Z)	Z	erf(Z)	Z	erf(Z)	Z	erf(Z)
0.00	0.000000000	0.50	0.520499878	1.00	0.842700793	1.50	0.966105146
0.01	0.011283416	0.51	0.529243620	1.01	0.846810496	1.51	0.967276748
0.02	0.022564575	0.52	0.537898630	1.02	0.850838018	1.52	0.968413497
0.03	0.033841222	0.53	0.546464097	1.03	0.854784211	1.53	0.969516209
0.04	0.045111106	0.54	0.554939250	1.04	0.858649947	1.54	0.970585690
0.05	0.056371978	0.55	0.563323366	1.05	0.862436106	1.55	0.971622733
0.06	0.067621594	0.56	0.571615764	1.06	0.866143587	1.56	0.972628122
0.07	0.078857720	0.57	0.579815806	1.07	0.869773297	1.57	0.973602627
0.08	0.090078126	0.58	0.587922900	1.08	0.873326158	1.58	0.974547009
0.09	0.101280594	0.59	0.595936497	1.09	0.876803102	1.59	0.975462016
0.10	0.112462916	0.60	0.603856091	1.10	0.880205070	1.60	0.976348383
0.11	0.123622896	0.61	0.611681219	1.11	0.883533012	1.61	0.977206837
0.12	0.134758352	0.62	0.619411462	1.12	0.886787890	1.62	0.978038088
0.13	0.145867115	0.63	0.627046443	1.13	0.889970670	1.63	0.978842840
0.14	0.156947033	0.64	0.634585829	1.14	0.893082328	1.64	0.979621780
0.15	0.167995971	0.65	0.642029327	1.15	0.896123843	1.65	0.980375585
0.16	0.179011813	0.66	0.649376688	1.16	0.899096203	1.66	0.981104921
0.17	0.189992461	0.67	0.656627702	1.17	0.902000399	1.67	0.981810442
0.18	0.200935839	0.68	0.663782203	1.18	0.904837427	1.68	0.982492787
0.19	0.211839892	0.69	0.670840062	1.19	0.907608286	1.69	0.983152587
0.20	0.222702589	0.70	0.677801194	1.20	0.910313978	1.70	0.983790459
0.21	0.233521923	0.71	0.684665550	1.21	0.912955508	1.71	0.984407008
0.22	0.244295912	0.72	0.691433123	1.22	0.915533881	1.72	0.985002827
0.23	0.255022600	0.73	0.698103943	1.23	0.918050104	1.73	0.985578500
0.24	0.265700059	0.74	0.704678078	1.24	0.920505184	1.74	0.986134595
0.25	0.276326390	0.75	0.711155634	1.25	0.922900128	1.75	0.986671671
0.26	0.286899723	0.76	0.717536753	1.26	0.925235942	1.76	0.987190275
0.27	0.297418219	0.77	0.723821614	1.27	0.927513629	1.77	0.987690942
0.28	0.307880068	0.78	0.730010431	1.28	0.929734193	1.78	0.988174196
0.29	0.318283496	0.79	0.736103454	1.29	0.931898633	1.79	0.988640549
0.30	0.328626759	0.80	0.742100965	1.30	0.934007945	1.80	0.989090502
0.31	0.338908150	0.81	0.748003281	1.31	0.936063123	1.81	0.989524545
0.32	0.349125995	0.82	0.753810751	1.32	0.938065155	1.82	0.989943156
0.33	0.359278655	0.83	0.759523757	1.33	0.940015026	1.83	0.990346805
0.34	0.369364529	0.84	0.765142711	1.34	0.941913715	1.84	0.990735948
0.35	0.379382054	0.85	0.770668058	1.35	0.943762196	1.85	0.991111030
0.36	0.389329701	0.86	0.776100268	1.36	0.945561437	1.86	0.991472488
0.37	0.399205984	0.87	0.781439845	1.37	0.947312398	1.87	0.991820748
0.38	0.409009453	0.88	0.786687319	1.38	0.949016035	1.88	0.992156223
0.39	0.418738700	0.89	0.791843247	1.39	0.950673296	1.89	0.992479318
0.40	0.428392355	0.90	0.796908212	1.40	0.952285120	1.90	0.992790429
0.41	0.437969090	0.91	0.801882826	1.41	0.953852439	1.91	0.993089940
0.42	0.447467618	0.92	0.806767722	1.42	0.955376179	1.92	0.993378225
0.43	0.456886695	0.93	0.811563559	1.43	0.956857253	1.93	0.993655650
0.44	0.466225115	0.94	0.816271019	1.44	0.958296570	1.94	0.993922571
0.45	0.475481720	0.95	0.820890807	1.45	0.959695026	1.95	0.994179334
0.46	0.484655390	0.96	0.825423650	1.46	0.961053510	1.96	0.994426275
0.47	0.493745051	0.97	0.829870293	1.47	0.962372900	1.97	0.994663725
0.48	0.502749671	0.98	0.834231504	1.48	0.963654065	1.98	0.994892000
0.49	0.511668261	0.99	0.838508070	1.49	0.964897865	1.99	0.995111413

Z	erf(Z)	Z	erf(Z)	Z	erf(Z)	Z	erf(Z)
2.00	0.995322265	2.50	0.999593048	3.00	0.999977910	3.50	0.999999257
2.01	0.995524849	2.51	0.999614295	3.01	0.999979261	3.51	0.999999309
2.02	0.995719451	2.52	0.999634501	3.02	0.999980534	3.52	0.999999358
2.03	0.995906348	2.53	0.999653714	3.03	0.999981732	3.53	0.999999403
2.04	0.996085810	2.54	0.999671979	3.04	0.999982859	3.54	0.999999445
2.05	0.996258096	2.55	0.999689340	3.05	0.999983920	3.55	0.999999485
2.06	0.996423462	2.56	0.999705837	3.06	0.999984918	3.56	0.999999521
2.07	0.996582153	2.57	0.999721511	3.07	0.999985857	3.57	0.999999555
2.08	0.996734409	2.58	0.999736400	3.08	0.999986740	3.58	0.999999587
2.09	0.996880461	2.59	0.999750539	3.09	0.999987571	3.59	0.999999617
2.10	0.997020533	2.60	0.999763966	3.10	0.999988351	3.60	0.999999644
2.11	0.997154845	2.61	0.999776711	3.11	0.999989085	3.61	0.999999670
2.12	0.997283607	2.62	0.999788809	3.12	0.999989774	3.62	0.999999694
2.13	0.997407023	2.63	0.999800289	3.13	0.999990422	3.63	0.999999716
2.14	0.997525293	2.64	0.999811181	3.14	0.999991030	3.64	0.999999736
2.15	0.997638607	2.65	0.999821512	3.15	0.999991602	3.65	0.999999756
2.16	0.997747152	2.66	0.999831311	3.16	0.999992138	3.66	0.999999773
2.17	0.997851108	2.67	0.999840601	3.17	0.999992642	3.67	0.999999790
2.18	0.997950649	2.68	0.999849409	3.18	0.999993115	3.68	0.999999805
2.19	0.998045943	2.69	0.999857757	3.19	0.999993558	3.69	0.999999820
2.20	0.998137154	2.70	0.999865667	3.20	0.999993974	3.70	0.999999833
2.21	0.998224438	2.71	0.999873162	3.21	0.999994365	3.71	0.999999845
2.22	0.998307948	2.72	0.999880261	3.22	0.999994731	3.72	0.999999857
2.23	0.998387832	2.73	0.999886985	3.23	0.999995074	3.73	0.999999867
2.24	0.998464231	2.74	0.999893351	3.24	0.999995396	3.74	0.999999877
2.25	0.998537283	2.75	0.999899378	3.25	0.999995697	3.75	0.999999886
2.26	0.998607121	2.76	0.999905082	3.26	0.999995980	3.76	0.999999895
2.27	0.998673872	2.77	0.999910480	3.27	0.999996245	3.77	0.999999903
2.28	0.998737661	2.78	0.999915587	3.28	0.999996493	3.78	0.999999910
2.29	0.998798606	2.79	0.999920418	3.29	0.999996725	3.79	0.999999917
2.30	0.998856823	2.80	0.999924987	3.30	0.999996942	3.80	0.999999923
2.31	0.998912423	2.81	0.999929307	3.31	0.999997146	3.81	0.999999929
2.32	0.998965513	2.82	0.999933390	3.32	0.999997336	3.82	0.999999934
2.33	0.999016195	2.83	0.999937250	3.33	0.999997515	3.83	0.999999939
2.34	0.999064570	2.84	0.999940898	3.34	0.999997681	3.84	0.999999944
2.35	0.999110733	2.85	0.999944344	3.35	0.999997838	3.85	0.999999948
2.36	0.999154777	2.86	0.999947599	3.36	0.999997983	3.86	0.999999952
2.37	0.999196790	2.87	0.999950673	3.37	0.999998120	3.87	0.999999956
2.38	0.999236858	2.88	0.999953576	3.38	0.999998247	3.88	0.999999959
2.39	0.999275064	2.89	0.999956316	3.39	0.999998367	3.89	0.999999962
2.40	0.999311486	2.90	0.999958902	3.40	0.999998478	3.90	0.999999965
2.41	0.999346202	2.91	0.999961343	3.41	0.999998582	3.91	0.999999968
2.42	0.999379283	2.92	0.999963645	3.42	0.999998679	3.92	0.999999970
2.43	0.999410802	2.93	0.999965817	3.43	0.999998770	3.93	0.999999973
2.44	0.999440826	2.94	0.999967866	3.44	0.999998855	3.94	0.999999975
2.45	0.999469420	2.95	0.999969797	3.45	0.999998934	3.95	0.999999977
2.46	0.999496646	2.96	0.999971618	3.46	0.999999008	3.96	0.999999979
2.47	0.999522566	2.97	0.999973334	3.47	0.999999077	3.97	0.999999980
2.48	0.999547236	2.98	0.999974951	3.48	0.999999141	3.98	0.999999982
2.49	0.999570712	2.99	0.999976474	3.49	0.999999201	3.99	0.999999983

Example #1

- Starting with n-type Si<100>, $N_D=10^{14}\text{cm}^{-3}$, how long do we need to to a “infinite source” B diffusion at 1000°C to make a junction depth (x_j) equal to $.5 \times 10^{-4}$ cm?

Example #2

- Starting with p-type Si<111>, $N_A=10^{15}\text{cm}^{-3}$, how deep will the junction depth (x_j in cm) if we do an “infinite source” P *pre-dep* diffusion at 1000°C for 10 minutes?
- What will be the junction depth (x_j in cm) if we do an “finite source” P *drive in* diffusion at 1000°C for 30 minutes?