

NEUTRON TRANSMUTATION DOPING OF SEMICONDUCTORS

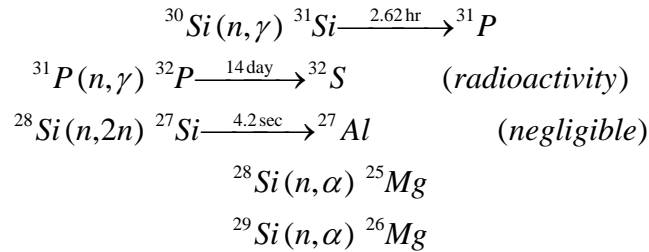
Neutron transmutation doping (NTD) is the process of creating non-radioactive impurity isotopes from the host atoms of a material by thermal neutron irradiation and subsequent radioactive decay. This technique is particularly applicable to doping semiconductors in cases of

1. better control on the spatial uniformity of doping, and
2. where a very small amount of dopant must be added.

Silicon Transmutation

The basic concept of doping silicon (Si) by creating phosphorous (P) atoms by the absorption of thermal neutrons was discussed in 1961 by Tanenbaum and Mills.[1] Significant commercial use of NTD Si started in the mid-1970s.

The primary and secondary nuclear reactions are



The capture cross section (σ) for P-31 is around 0.19 barn. The radioactivity produced from the P-31 transmutation, or any other trace impurity initially in the silicon, can lead to abnormally long half-life activities, which may require that the doped material be held from device production until sufficient decay has been reached.

Silicon NTD Nuclear Properties [2]

Isotope	Abundance ω (%)	Neutron capture cross section (b)	Neutron capture and β - decay reactions	Dopant type
${}^{28}\text{Si}$	92.3	0.08	${}^{28}\text{Si}(n, \gamma) {}^{29}\text{Si}$	
${}^{29}\text{Si}$	4.7	0.28	${}^{29}\text{Si}(n, \gamma) {}^{30}\text{Si}$	
${}^{30}\text{Si}$	3.1	0.11	${}^{30}_{14}\text{Si}(n, \gamma) {}^{31}_{14}\text{Si} \xrightarrow{2.62\text{hr}} {}^{31}_{15}\text{P}$	n

The concentration of dopant phosphorus (P), generated by neutron capture, is given by

$$N_P = \int_0^{t_I} \int_0^{\infty} N_{30} \sigma_{30}(E) \phi(E, t) dE dt = N_{Si-30} \sigma \phi t_I$$

Direct determination of the induced P-31 concentrations in NTD Si may be obtained by measurements of absolute Si-31 activity by detection of the 1.266 MeV gamma rays that are emitted (based on the γ -ray abundance). The ratio of P dopant to Si is

$$\frac{N_P}{N_{Si}} = \frac{N_P}{N_{Si-30} / \omega_{Si-30}} = \omega_{30} \sigma_{30} \phi t_I = (0.031)(0.11) \phi t_I = 0.0034 \phi t_I$$

Thus, by increasing the neutron flux (ϕ) or irradiation time (t_I), the dopant fraction is increased.

Several radiation damage mechanisms contribute to the displacement of the silicon atoms from their normal lattice positions:

1. fast neutron knock-on displacements from elastic scattering
2. fission gamma induced damage
3. gamma recoil damage from thermal neutron capture
4. beta recoil damage
5. charged particle knock-ons from (n,p) , (n,α) , etc. reactions

The gamma and charged particle mechanisms (items 2 & 5 above) can be neglected compared to the others.

The secondary reaction products of sulfur (via thermal neutron absorption) and magnesium (from fast neutrons) are expected to reduce the minority-carrier lifetime because they create deep lying levels in the silicon energy gap which constitute recombination centers. Also, the silicon lattice is damaged due to gamma recoil and irradiation by β decay particles from Si-31. The fast neutron flux can also create localized damage clusters which might influence the diffusion during device fabrication, and which consequently would severely degrade device breakdown voltage. These problems can be overcome by adequate thermal annealing procedures prior to device fabrication.[4] At sufficiently high temperatures the irradiation produced defects (from fast neutrons) become mobile and can be removed. Atomic displacement effects due to NTD are addressed by Stein.[3]

Typically, NTD-Si is used in power semiconductor devices that operate at high currents and voltages. The fabrication of these devices requires high resistivity silicon wafers with good spatial uniformity over large areas (which is needed to achieve the current-carrying capability). Development of NTD Si has led to substantial improvements in the yield of high-voltage power rectifiers and thyristors. The greater spatial uniformity, as well as the precise control over the resistivity achievable by using the NTD process, has led to a substantial increase in the breakdown voltage capability of thyristors.[4] The homogeneity in NTD-Si is a result of a homogeneous distribution of silicon isotopes in the target material and the long range of neutrons in silicon.

The advantages of NTD are

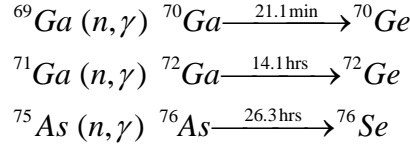
1. precision target doping ($\approx 1\%$ or better)
2. better axial and radial uniformity
3. no microresistivity structure

The disadvantages of NTD are

1. irradiation costs
2. reduction in minority carrier lifetime
3. radioactive safeguards considerations

Gallium Arsenide (GaAs) Transmutation [5]

Since the (n,α) , (n,p) and $(n,2n)$ reactions, as well as the fast neutron reactions, can be neglected[6], the effect of transmutation doping of GaAs is to introduce germanium (Ge) and selenium (Se) impurities. Neutron transmutation doping of gallium arsenide (GaAs) is based on the following thermal neutron capture reactions



In [5], a neutron flux of 4×10^{12} n/cm²·sec was used, with irradiation times of 2 to 185 hours.

Gallium Arsenide NTD Nuclear Properties [7,8]

Isotope	Abundance (%)	Neutron capture cross section (b)	Neutron capture and β - decay reactions	Dopant type
⁶⁹ Ga	60.0	1.8	${}_{31}^{69}\text{Ga} (n, \gamma) {}_{31}^{70}\text{Ga} \xrightarrow{21.1\text{min}} {}_{32}^{70}\text{Ge}$	n
⁷¹ Ga	40.0	0.15	${}_{31}^{71}\text{Ga} (n, \gamma) {}_{31}^{72}\text{Ga} \xrightarrow{14.1\text{hrs}} {}_{32}^{72}\text{Ge}$	n
⁷⁵ As	100.0	4.30	${}_{33}^{75}\text{As} (n, \gamma) {}_{33}^{76}\text{As} \xrightarrow{26.3\text{hrs}} {}_{34}^{76}\text{Se}$	n

The concentrations of Ge and Se produced are

$$\begin{aligned} N_{\text{Ge}} &= [\omega_{69} \sigma_{69} + \omega_{71} \sigma_{71}] N_{\text{GaAs}} \phi t_I \\ N_{\text{Se}} &= \sigma_{75} N_{\text{GaAs}} \phi t_I \end{aligned}$$

where ω_k is the isotopic abundance of k , and $N_{\text{GaAs}} = N_{\text{Ga}} = N_{\text{As}}$.

On the basis of tabulated abundances and cross-sections, the ratio of Se and Ge dopant to original material is

$$\begin{aligned} \frac{N_{\text{Se}} + N_{\text{Ge}}}{N_{\text{GaAs}}} &= [\sigma_{75} + \omega_{69} \sigma_{69} + \omega_{71} \sigma_{71}] \phi t_I \\ &= [4.3 + (0.6)(1.8) + (0.4)(0.15)] \phi t_I = 5.44 \phi t_I \end{aligned}$$

The relative abundances of the isotopes involved in the reactions, and the cross sections for these reactions are such that the ratio of Se dopant to Ge dopant is

$$\frac{N_{\text{Se}}}{N_{\text{Ge}}} = \frac{\sigma_{75}}{\omega_{69} \sigma_{69} + \omega_{71} \sigma_{71}} = \frac{4.3}{(0.6)(1.8) + (0.4)(0.15)} = 3.77$$

which is independent of the flux and irradiation time. The attainable dopant concentrations are almost 1000 times higher in GaAs than in silicon. Alternatively, the ratio of Se and Ge concentrations produced is equivalent to the capture cross sections of the two elements, that is,

$$\frac{N_{\text{Se}}}{N_{\text{Ge}}} = \frac{\sigma_{\text{As}}}{\sigma_{\text{Ga}}} = \frac{4.3}{3.1} = 1.39$$

There is a fair amount of discrepancy between the two values, which lies in the inaccuracy of the cross section information.

Germanium (Ge) Transmutation

Germanium NTD Nuclear Properties [9]

Isotope	Abundance (%)	Neutron capture cross section (b)	Neutron capture and decay reactions	Dopant type
^{70}Ge	20.5	3.2-3.4	$^{70}_{32}\text{Ge} (n, \gamma) ^{71}_{32}\text{Ge} \xrightarrow{11.2 \text{ days}} ^{71}_{31}\text{Ga}$	p
^{72}Ge	27.4	0.98-1.0	$^{72}\text{Ge} (n, \gamma) ^{73}\text{Ge}$	
^{73}Ge	7.8	14.0-15.0	$^{73}\text{Ge} (n, \gamma) ^{74}\text{Ge}$	
^{74}Ge	36.5	0.5-0.62	$^{74}_{32}\text{Ge} (n, \gamma) ^{75}_{32}\text{Ge} \xrightarrow{82.8 \text{ min}} ^{75}_{33}\text{As}$	n
^{76}Ge	7.8	0.16-0.36	$^{76}_{32}\text{Ge} (n, \gamma) ^{77}_{32}\text{Ge} \xrightarrow{11.3 \text{ hr}} ^{77}_{33}\text{As} \xrightarrow{38.8 \text{ hr}} ^{77}_{34}\text{Se}$	n

The ratio of Ga, As and Se dopant to Ge is

$$\frac{N_{Ga} + N_{As} + N_{Se}}{N_{Ge}} = [\omega_{70} \sigma_{70} + \omega_{74} \sigma_{74} + \omega_{76} \sigma_{76}] \phi t_i$$

$$= [(0.205)(3.3) + (0.365)(0.56) + (0.078)(0.26)] \phi t_i = 0.90 \phi t_i$$

The computation of acceptor to donor concentrations may be computed from

$$K = \frac{\sum \text{donors} / \text{cm}^3}{\sum \text{acceptors} / \text{cm}^3} = \frac{N_{As} + 2N_{Se}}{N_{Ga}} = \frac{\omega_{74} \sigma_{74} + 2(\omega_{76} \sigma_{76})}{\omega_{70} \sigma_{70}} = 0.362$$

where Se impurities are double donors providing 2 electrons for compensation. The attainable dopant concentrations are almost 100 times higher in Ge than in silicon.

Gallium Phosphide (GaP) Transmutation

Gallium Phosphide NTD Nuclear Properties [7,8]

Isotope	Abundance (%)	Neutron capture cross section (b)	Neutron capture and β - decay reactions	Dopant type
^{69}Ga	60.0	1.8	$^{69}_{31}\text{Ga} (n, \gamma) ^{70}_{31}\text{Ga} \xrightarrow{21.1 \text{ min}} ^{70}_{32}\text{Ge}$	n
^{71}Ga	40.0	0.15	$^{71}_{31}\text{Ga} (n, \gamma) ^{72}_{31}\text{Ga} \xrightarrow{14.1 \text{ hr}} ^{72}_{32}\text{Ge}$	n
^{31}P	100.0	0.19	$^{31}_{15}\text{P} (n, \gamma) ^{32}_{15}\text{P} \xrightarrow{14.3 \text{ day}} ^{32}_{16}\text{S}$	n

Selenium (Se) Transmutation

Selenium NTD Nuclear Properties [7,8]

Isotope	Abundance (%)	Neutron capture cross section (b)	Neutron capture and β -decay reactions	Dopant type
^{74}Se	0.9	55	$^{74}_{34}\text{Se} (n, \gamma) ^{75}_{34}\text{Se} \xrightarrow{120.4 \text{ day}} ^{75}_{33}\text{As}$	p
^{76}Se	9.0	21	$^{76}\text{Se} (n, \gamma) ^{77}\text{Se}$	
^{77}Se	7.6	42	$^{77}\text{Se} (n, \gamma) ^{78}\text{Se}$	
^{78}Se	23.5	0.20-0.33	$^{78}_{34}\text{Se} (n, \gamma) \left\{ \begin{array}{l} ^{79m}_{34}\text{Se} \xrightarrow{? \text{ sec}} \\ ^{79}_{34}\text{Se} \xrightarrow{65,000 \text{ yrs}} \end{array} \right\} ^{79}_{33}\text{As} \rightarrow \dots$	
^{80}Se	49.8	0.08	$^{80}_{34}\text{Se} (n, \gamma) ^{81}_{34}\text{Se} \xrightarrow{18.6 \text{ min}} ^{81}_{33}\text{As} \rightarrow \dots$	
^{82}Se	9.2	6-40	$^{82}_{34}\text{Se} (n, \gamma) \left\{ \begin{array}{l} ^{83m}_{34}\text{Se} \xrightarrow{70 \text{ sec}} \\ ^{83}_{34}\text{Se} \xrightarrow{23 \text{ min}} \end{array} \right\} ^{83}_{33}\text{As} \rightarrow \dots$	

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