



Designation: F 723 – 99

Standard Practice for Conversion Between Resistivity and Dopant Density for Boron-Doped, Phosphorus-Doped, and Arsenic-Doped Silicon¹

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INTRODUCTION

The ability to convert between resistivity and dopant density in a semiconductor is important for a variety of applications ranging from material inspection and acceptance to process and device modeling. Despite some experimental limitations, the conversion is more readily established from an empirical data base than from theoretical calculations. Resistivity may be unambiguously determined throughout the desired resistivity range regardless of the dopant impurity. However, it was necessary to use a variety of techniques to establish the complete dopant density scale of interest; these techniques do not all respond to the same parameter of the semiconductor.

In the experimental work (1), (2), (3)² supporting these conversions, capacitance-voltage measurements were used to determine the dopant density of both boron- and phosphorous-doped specimens with dopant densities less than about 10^{18} cm^{-3} . The specimens were assumed to be negligibly compensated; hence, the data given by the capacitance-voltage measurements were taken to be a direct measure of the dopant density in the specimen. Hall effect measurements were used to obtain dopant density values greater than 10^{18} cm^{-3} . In addition, in this range neutron activation analysis and spectrophotometric analysis were used to determine phosphorus density, and the nuclear track technique was used to determine boron density. Where there were discrepancies in the data from the analytical techniques, more weight was given to the Hall effect results. Up to the highest densities measured, boron is expected to be fully electrically active. Therefore, the boron densities of these specimens were assumed equal to the carrier densities obtained from the Hall effect measurements with the use of an estimate for the Hall proportionality factor based on the best available experimental and theoretical information. In the case of specimens heavily doped with phosphorus, the Hall proportionality factor is unity, but there is considerable evidence that at densities above about $5 \times 10^{19} \text{ cm}^{-3}$ not all of the phosphorus is electrically active because of the formation of complexes. In the absence of data regarding the fraction of phosphorus atoms withdrawn from electrically active states due to complexing, the values of carrier density taken from the Hall effect measurements were assumed to be equal to the phosphorus density values. Consequently, the conversions based on these data may understate the total phosphorus density for stated values above about $5 \times 10^{19} \text{ cm}^{-3}$.



1. Scope

1.1 This practice³ describes a conversion between dopant density and resistivity for arsenic-, boron- and phosphorus-doped single crystal silicon at 23°C. The conversions are based primarily on the data of Thurber et al (1), (2), (3)³ taken on bulk single crystal silicon having dopant density values in the range from $3 \times 10^{13} \text{ cm}^{-3}$ to $1 \times 10^{20} \text{ cm}^{-3}$ for phosphorus-doped silicon and in the range from 10^{14} cm^{-3} to $1 \times 10^{20} \text{ cm}^{-3}$ for boron-doped silicon. The phosphorus data base was supplemented in the following manner: two bulk specimen data points of Esaki and Miyahara (4) and one diffused specimen data point of Fair and Tsai (5) were used to extend the data base above 10^{20} cm^{-3} , and an imaginary point was added at 10^{12} cm^{-3} to improve the quality of the conversion for low dopant density values. A conversion for arsenic, distinct from that of phosphorus, is presented for the range 10^{19} to $6 \times 10^{20} \text{ cm}^{-3}$.

1.2 The self consistency of the conversion (resistivity to dopant density and dopant density to resistivity) (see Appendix X1) is within 3 % for boron from 0.0001 to $10\,000 \Omega \cdot \text{cm}$ (10^{12} to 10^{21} cm^{-3}) and within 4.5 % for phosphorus from 0.0002 to $4000 \Omega \cdot \text{cm}$ (10^{12} to $5 \times 10^{20} \text{ cm}^{-3}$). This error increases rapidly if the phosphorus conversions are used for densities above $5 \times 10^{20} \text{ cm}^{-3}$.

1.3 These conversions are based upon boron and phosphorus data. They may be extended to other dopants in silicon that have similar activation energies; although the accuracy of conversions for other dopants has not been established, it is expected that the phosphorus data would be satisfactory for use with arsenic and antimony, except when approaching solid solubility (see 6.3).

1.4 These conversions are between resistivity and dopant density and should not be confused with conversions between resistivity and carrier density or with mobility relations.

NOTE 1—The commonly used conversion between resistivity and dopant density compiled by Irvin (6) is compared with this conversion in Appendix X2. In this compilation, Irvin used the term “impurity concentration” instead of the term “dopant density.”

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

F 84 Test Method for Measuring Resistivity of Silicon

¹ This practice is under the jurisdiction of ASTM Committee F-1 on Electronics and is the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Control.

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² Boldface numbers in parentheses refer to the list of references at the end of this practice.

³ DIN 50434 is an equivalent method. It is the responsibility of DIN Committee NMP 221, with which Committee F-1 maintains close technical liaison. DIN 50444, Testing of Materials for Semiconductor Technology: Conversion Between Resistivity and Dopant Density of Silicon, is available from Beuth Verlag GmbH Burggrafenstrasse 4-10, D-1000 Berlin 30, Federal Republic of Germany.

Wafers with an In-Line Four-Point Probe⁴

2.2 ASTM Adjuncts:

Large Wall Chart⁵

3. Terminology

3.1 Definitions:

3.1.1 *carrier density*, n (electrons); p (holes)—the number of majority carriers per unit volume in an extrinsic semiconductor, usually given in number/ cm^3 although the SI unit is number/ m^3 .

3.1.2 *compensation*—reduction in number of free carriers resulting from the presence of impurities other than the majority dopant density impurity. Compensation occurs when both donor and acceptor dopant impurities are present in a semiconductor; in this case the net dopant density (which is equal to the carrier density provided that all the dopant impurities are ionized) is given by the absolute magnitude of the difference between the acceptor dopant density and the donor dopant density. Compensation may also occur if deep-level impurities or defects are present in quantities comparable with the dopant impurities; in this case the relationship between the carrier density and the dopant density (under the assumption of full ionization of the dopant impurity) depends on a variety of parameters (7). A semiconductor that exhibits compensation is said to be “compensated.”

3.1.3 *concentration*—relative amount of a minority constituent of a mixture to the majority constituent (for example, parts per million, parts per billion, or percent) by either volume or weight. In the semiconductor literature, often used interchangeably with number density (for example, number per unit volume).

3.1.4 *deep-level impurity*—a chemical element that when introduced into a semiconductor has an energy level (or levels) that lies in the mid-range of the forbidden energy gap, between those of the dopant impurity species.

3.1.4.1 *Discussion*—Certain crystal defects and complexes may also introduce electrically active deep levels in the semiconductor.

3.1.5 *dopant density*—in an uncompensated extrinsic semiconductor, the number of dopant impurity atoms per unit volume, usually given in atoms/ cm^3 although the SI unit is atoms/ m^3 . Symbols: N_D for donor impurities and N_A for acceptor impurities.

4. Summary of Practice

4.1 The conversions between resistivity and dopant density are made using equations, tables, or graphs.

5. Significance and Use

5.1 Dopant density and resistivity of silicon are two important acceptance parameters used in the interchange of material by consumers and producers in the semiconductor industry. Therefore, a particular method of converting from dopant

⁴ Annual Book of ASTM Standards, Vol 10.05.

⁵ A large wall chart, “Conversion Between Resistivity and Dopant Density” is available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428. Order Adjunct ADJF0723.





density to resistivity and vice versa must be available since some test methods measure resistivity while others measure dopant density.

5.2 These conversions are useful in mathematical modeling of semiconductor processing and devices.

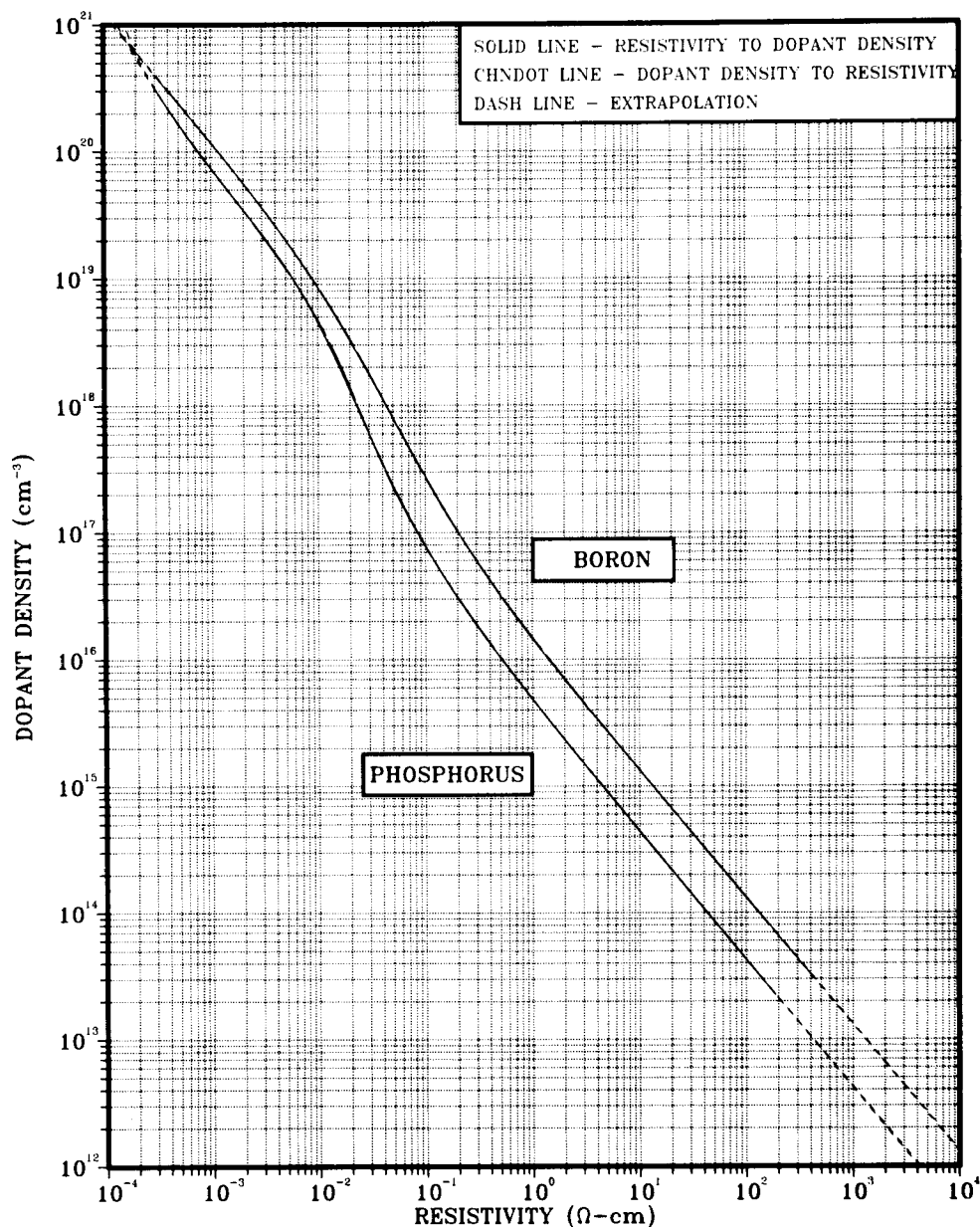
6. Interferences

6.1 *Carrier Density*— Attempts to derive carrier density

values from resistivity values by using these conversions are subject to error. While dopant density and carrier density values are expected to be the same at low densities (up to about 10^{17} cm^{-3}), the two quantities generally do not have the same value in a given specimen at moderate densities. At such moderate densities, (about 10^{17} cm^{-3} to 10^{19} cm^{-3}), dopant densities are larger than carrier densities due to incomplete

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NOTE 1—The solid line shows the resistivity to dopant density conversion for the range of actual data. The chain dot line shows the dopant density to resistivity conversion for the range of actual data. Dashed lines show regions of extrapolation from data.

NOTE 2—On the scale of the figure as reproduced in this book, the solid and chain-dot lines cannot be distinguished visually. They are distinguishable, however, on the wall chart available as Adjunct PCN 12-607230-46, wherever the self-consistency error (see Appendix X1) becomes appreciable.

FIG. 1 Preferred Conversion Between Resistivity and Total Dopant Density Values for Boron- and Phosphorus-Doped Silicon



ionization. At densities above 10^{19} cm^{-3} , the population statistics become degenerate, and carrier densities would normally be equal to dopant densities. However, in this upper range of densities, the possibility of formation of compounds or complexes involving dopant atoms is more pronounced and would prevent some of the dopant atoms from being electrically active. Such formation of compounds or complexes is particularly likely in phosphorus- or arsenic-doped silicon. Precipitation occurs at dopant densities greater than solid solubility.

6.2 Heavily Phosphorus-Doped Silicon—These conversions are given as functions of resistivity and of dopant density. For heavily phosphorus-doped specimens, primary emphasis was placed on Hall effect measurements for establishing the density values. However, since the Hall effect measures carrier density, it was assumed for these heavily doped specimens that all atoms were electrically active; that is, the dopant density was equal to the carrier density as measured by the Hall effect. The possible formation of phosphorus-vacancy pairs which are known to reduce the electrically active phosphorus atoms at high densities (5) was not tested or accounted for in the data base or the resulting conversions. The existence of such phosphorus-vacancy pairs would cause the Hall measurements to understate the total dopant density for the heavily phosphorus-doped specimens.

6.3 Other Dopant Species—The applicability of these conversions to silicon doped with other than arsenic, boron or phosphorus has not yet been established. However, in the lightly doped range ($<10^{17} \text{ cm}^{-3}$) the conversions are expected to be reasonably accurate for other dopants. Between 10^{17} and 10^{19} cm^{-3} , the difference in activation energy of different dopant species will cause different resistivities to be measured for the same dopant density. In this range the differences in resistivities will be larger among the *p*-type dopants than among the *n*-type dopants due to larger differences in the activation energies among the *p*-type dopants. At high dopant densities ($>10^{19} \text{ cm}^{-3}$), the formation of complexes involving dopant atoms, lattice defects, and other impurities will lead to a modification in the number of charge carriers. The extent of this effect will depend upon the particular dopant species and is not well detailed in the literature for the various common dopants. Its onset is expected to be related to the density of the dopant compared to the solid solubility of that dopant in silicon. Therefore, in this upper dopant density range, the applicability of these conversions to dopants other than boron and phosphorus is unclear.

6.4 Compensation—The specimens used to obtain the data base for these conversions were assumed to be uncompensated. The measured net dopant density was taken to be the total density of the intentional dopant in the specimen. For specimens in which significant compensation occurs, these conversions may not apply.

6.5 Temperature—The conversions in this practice hold for a temperature of 23°C. Resistivity varies with temperature, but dopant density does not.

NOTE 2—It is possible to obtain dopant density values from resistivity values that were not measured at 23°C by using Test Method F 84 to correct the resistivity values to 23°C. Also, the conversion from dopant density to resistivity may be made directly and the temperature correction for resistivity then made following Test Method F 84 to obtain the resistivity at other than 23°C.

NOTE 3—References 1, 2, and 3 give values for the coefficients in the conversion equations at both 23°C and 300 K.

6.6 Other Electrically Active Centers—Numerous other mechanisms exist that may modify the number of free carriers or noticeably alter carrier mobility, either of which will change the resistivity from the value given here for a given dopant density. Among these mechanisms are (1) lattice damage due to radiation (neutron transmutation doping or ion implantation), (2) formation of deep level centers due to chemical impurities (typically heavy metals, either unwanted or sometimes intentionally added for minority carrier lifetime control), and (3) unintentional doping due, for example, to electrically activated oxygen. When any of these effects is known or expected to be present, the conversions given here may not apply.

6.7 Range of Arsenic-Doped Silicon Data—The conversion given for arsenic-doped silicon is from Fair and Tsai (8), covering the doping range of 10^{19} to 6×10^{20} . This conversion was generated using Hall effect measurements. The principal reference for neutron activation data is that of Newman *et al.* (9). Neutron activation data give higher resistivity values for a given dopant density than do Hall data because of the assumption that the Hall coefficient $R_H = 1/ne$. A more complicated relationship between R_H and n is given in Ref (9). Care must be taken in using any conversion not to extrapolate beyond the range of the data fitted, as the formulas will diverge beyond that range. Other studies support the use of the conversion given here Refs (10, 11, 12, and 13), which means that the conversion to resistivity for phosphorus can be used for arsenic in this range. In the range 2×10^{19} to 10^{20} , the Fair and Tsai fit matches the Irvin formula. The range beyond 6×10^{20} is discussed only in Ref (13).

7. Procedure

7.1 Convert Resistivity Values to Dopant Density Values—Follow 7.1.1 (graphical method), 7.1.2 (tabular method), or 7.1.3 (computation method).⁵

7.1.1 Graphical Method:

7.1.1.1 For boron-doped silicon, use the curve labeled “boron” in Fig. 1.

7.1.1.2 For phosphorus-doped silicon, use the curve labeled “phosphorus” in Fig. 1.

7.1.2 Tabular Method:

7.1.2.1 For boron-doped silicon use Table 1.



TABLE 1 Dopant Density as a Function of Resistivity for Boron-Doped Silicon

NOTE 1—Entries in two significant digits are for regions of extrapolated data.

RESISTIVITY (Ω -cm)	DOPANT DENSITY (cm^{-3})										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
1.0E-04	1.2E21	1.1E21	1.0E21	9.3E20	8.6E20	8.1E20	7.6E20	7.1E20	6.7E20	6.4E20	BORON
2.0E-04	6.0E20	5.8E20	5.5E20	5.2E20	5.0E20	4.8E20	4.6E20	4.5E20	4.3E20	4.2E20	BORON
3.0E-04	4.01E20	3.88E20	3.76E20	3.64E20	3.54E20	3.43E20	3.34E20	3.25E20	3.16E20	3.08E20	BORON
4.0E-04	3.00E20	2.93E20	2.85E20	2.79E20	2.72E20	2.66E20	2.60E20	2.55E20	2.49E20	2.44E20	BORON
5.0E-04	2.39E20	2.34E20	2.30E20	2.25E20	2.21E20	2.17E20	2.13E20	2.09E20	2.06E20	2.02E20	BORON
6.0E-04	1.99E20	1.95E20	1.92E20	1.89E20	1.86E20	1.83E20	1.80E20	1.77E20	1.75E20	1.72E20	BORON
7.0E-04	1.70E20	1.67E20	1.65E20	1.62E20	1.60E20	1.58E20	1.56E20	1.54E20	1.52E20	1.50E20	BORON
8.0E-04	1.48E20	1.46E20	1.44E20	1.42E20	1.41E20	1.39E20	1.37E20	1.36E20	1.34E20	1.32E20	BORON
9.0E-04	1.31E20	1.29E20	1.28E20	1.27E20	1.25E20	1.24E20	1.22E20	1.21E20	1.20E20	1.19E20	BORON
1.0E-03	1.17E20	1.06E20	9.70E19	8.92E19	8.25E19	7.67E19	7.17E19	6.72E19	6.32E19	5.97E19	BORON
2.0E-03	5.65E19	5.36E19	5.09E19	4.85E19	4.63E19	4.43E19	4.24E19	4.07E19	3.91E19	3.76E19	BORON
3.0E-03	3.62E19	3.49E19	3.37E19	3.25E19	3.15E19	3.04E19	2.95E19	2.86E19	2.77E19	2.69E19	BORON
4.0E-03	2.61E19	2.54E19	2.47E19	2.40E19	2.34E19	2.28E19	2.22E19	2.17E19	2.11E19	2.06E19	BORON
5.0E-03	2.01E19	1.97E19	1.92E19	1.88E19	1.84E19	1.80E19	1.76E19	1.72E19	1.69E19	1.65E19	BORON
6.0E-03	1.62E19	1.59E19	1.56E19	1.53E19	1.50E19	1.47E19	1.44E19	1.41E19	1.39E19	1.36E19	BORON
7.0E-03	1.34E19	1.32E19	1.29E19	1.27E19	1.25E19	1.23E19	1.21E19	1.19E19	1.17E19	1.15E19	BORON
8.0E-03	1.13E19	1.11E19	1.10E19	1.08E19	1.06E19	1.05E19	1.03E19	1.02E19	1.00E19	9.88E18	BORON
9.0E-03	9.74E18	9.60E18	9.47E18	9.33E18	9.20E18	9.08E18	8.95E18	8.83E18	8.72E18	8.60E18	BORON
1.0E-02	8.49E18	7.48E18	6.65E18	5.97E18	5.39E18	4.89E18	4.47E18	4.10E18	3.78E18	3.49E18	BORON
2.0E-02	3.24E18	3.02E18	2.82E18	2.64E18	2.48E18	2.33E18	2.20E18	2.07E18	1.96E18	1.86E18	BORON
3.0E-02	1.77E18	1.68E18	1.60E18	1.53E18	1.46E18	1.40E18	1.34E18	1.28E18	1.23E18	1.18E18	BORON
4.0E-02	1.14E18	1.09E18	1.05E18	1.02E18	9.80E17	9.46E17	9.14E17	8.84E17	8.56E17	8.29E17	BORON
5.0E-02	8.03E17	7.79E17	7.55E17	7.33E17	7.12E17	6.92E17	6.73E17	6.55E17	6.37E17	6.21E17	BORON
6.0E-02	6.05E17	5.89E17	5.75E17	5.61E17	5.47E17	5.34E17	5.22E17	5.10E17	4.98E17	4.87E17	BORON
7.0E-02	4.76E17	4.66E17	4.56E17	4.47E17	4.37E17	4.29E17	4.20E17	4.12E17	4.03E17	3.96E17	BORON
8.0E-02	3.88E17	3.81E17	3.74E17	3.67E17	3.60E17	3.54E17	3.48E17	3.42E17	3.36E17	3.30E17	BORON
9.0E-02	3.24E17	3.19E17	3.14E17	3.09E17	3.04E17	2.99E17	2.94E17	2.90E17	2.85E17	2.81E17	BORON
1.0E-01	2.77E17	2.40E17	2.11E17	1.88E17	1.69E17	1.53E17	1.40E17	1.28E17	1.18E17	1.10E17	BORON
2.0E-01	1.02E17	9.59E16	9.01E16	8.49E16	8.02E16	7.60E16	7.22E16	6.88E16	6.56E16	6.27E16	BORON
3.0E-01	6.00E16	5.76E16	5.53E16	5.32E16	5.13E16	4.94E16	4.77E16	4.61E16	4.46E16	4.32E16	BORON
4.0E-01	4.19E16	4.07E16	3.95E16	3.84E16	3.73E16	3.63E16	3.54E16	3.45E16	3.36E16	3.28E16	BORON
5.0E-01	3.21E16	3.13E16	3.06E16	2.99E16	2.93E16	2.87E16	2.81E16	2.75E16	2.69E16	2.64E16	BORON
6.0E-01	2.59E16	2.54E16	2.49E16	2.45E16	2.40E16	2.36E16	2.32E16	2.28E16	2.24E16	2.21E16	BORON
7.0E-01	2.17E16	2.14E16	2.10E16	2.07E16	2.04E16	2.01E16	1.98E16	1.95E16	1.92E16	1.89E16	BORON
8.0E-01	1.87E16	1.84E16	1.82E16	1.79E16	1.77E16	1.75E16	1.72E16	1.70E16	1.68E16	1.66E16	BORON
9.0E-01	1.64E16	1.62E16	1.60E16	1.58E16	1.56E16	1.54E16	1.53E16	1.51E16	1.49E16	1.47E16	BORON
1.0E00	1.46E16	1.31E16	1.20E16	1.10E16	1.01E16	9.41E15	8.79E15	8.24E15	7.76E15	7.33E15	BORON
2.0E00	6.95E15	6.60E15	6.29E15	6.01E15	5.75E15	5.51E15	5.29E15	5.08E15	4.90E15	4.72E15	BORON
3.0F00	4.56E15	4.41E15	4.27E15	4.13E15	4.01E15	3.89E15	3.78E15	3.68E15	3.58E15	3.48E15	BORON
4.0E00	3.39E15	3.31E15	3.23E15	3.15E15	3.08E15	3.01E15	2.94E15	2.88E15	2.82E15	2.76E15	BORON
5.0F00	2.70E15	2.65E15	2.60E15	2.55E15	2.50E15	2.45E15	2.41E15	2.37E15	2.32E15	2.28E15	BORON
6.0E00	2.25E15	2.21E15	2.17E15	2.14E15	2.10E15	2.07E15	2.04E15	2.01E15	1.98E15	1.95E15	BORON
7.0F00	1.92E15	1.89E15	1.87E15	1.84E15	1.82E15	1.79E15	1.77E15	1.74E15	1.72E15	1.70E15	BORON
8.0E00	1.68E15	1.66E15	1.64E15	1.62E15	1.60E15	1.58E15	1.56E15	1.54E15	1.52E15	1.51E15	BORON
9.0F00	1.49E15	1.47E15	1.46E15	1.44E15	1.43E15	1.41E15	1.40E15	1.38E15	1.37E15	1.35E15	BORON