SEMI MF723-0307[E] (Reapproved 0412)[E]
PRACTICE FOR CONVERSION BETWEEN RESISTIVITY AND DOPANT OR CARRIER DENSITY FOR BORON-DOPED, PHOSPHORUS-DOPED, AND ARSENIC-DOPED SILICON

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[E] This Standard was editorially modified in November 2016 to correct a publication error during the 0412 reapproval. Changes were made to Equation 2.

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1 Purpose

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

1.2 In addition, there are occasions when conversion from resistivity to carrier density is required.

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

1.4 This Practice describes conversions between dopant density and resistivity for arsenic-, boron- and phosphorus-doped single crystal silicon and conversions from resistivity to carrier density for boron- and phosphorus doped single crystal silicon at 23°C.

NOTE 1: Except that it does not include dopant density conversions for arsenic-doped silicon or any carrier density conversions, DIN 50444 is an equivalent practice.

1.5 Despite some experimental limitations, the conversions are more readily established from an empirical database than from theoretical calculations.

1.5.1 The conversions for boron- and phosphorus-doped silicon in this Practice are based primarily on the data of Thurber *et al.*[1,2,3] taken on bulk single crystal silicon having dopant density values in the range from 3×10^{13} cm^{-3} to 1×10^{20} cm^{-3} for phosphorus-doped silicon and in the range from 10^{14} cm^{-3} to 1×10^{20} 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.

1.6 A limited additional conversion is given for arsenic-doped silicon, for the doping range 10^{19} to 6×10^{20} cm^{-3}, where it is shown to differ from the conversion for phosphorus-doped silicon, but it is only available in the direction from dopant density to resistivity. This conversion from Fair and Tsai[6] was generated using Hall effect measurements covering this dopant density range. Below this dopant density range, the conversion for phosphorus-doped silicon can be applied to arsenic-doped silicon.

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[1] Thurber, W. R., Mattis, R. L., Liu, Y. M., and Filliben, J. J. "Resistivity-Dopant Density Relationship for Phosphorus-Doped Silicon." *Journal of the Electrochemical Society*, Volume 127 (1980): pp. 1807–1812.

[2] Thurber, W. R., Mattis, R. L., Liu, Y. M., and Filliben, J. J. "Resistivity-Dopant Density Relationship for Boron-Doped Silicon." *Journal of the Electrochemical Society*, Volume 127 (1980): pp. 2291–2294.

[3] Thurber, W. R., Mattis, R. L., Liu, Y. M., and Filliben, J. J. *Semiconductor Measurement Technology*, "Relationship Between Resistivity and Dopant Density for Phosphorus- and Boron-Doped Silicon." NBS Special Publication 400-64, April 1981.

[4] Esaki, L., and Miyahara, Y. "A New Device Using the Tunneling Process in Narrow *p-n* Junction." *Solid-State Electronics*, Volume 1 (1960): pp. 13–21.

[5] Fair, R. B., and Tsai, J. C. C. "A Quantitative Model for the Diffusing of Phosphorus in Silicon and the Emitter Dip Effect." *Journal of the Electrochemical Society*, Volume 124 (1977): pp. 1107–1118.

[6] Fair, R. B., and Tsai, J. C. C. "The Diffusion of Ion-Implanted Arsenic in Silicon." *Journal of the Electrochemical Society*, Volume 122 (1975): p. 1689.

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NOTE 2: 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 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.

2 Scope

2.1 These conversions are based upon data from boron- and phosphorus-doped silicon. 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 ¶ 3.3).

2.2 Conversions between resistivity and dopant density should not be confused with conversions between resistivity and carrier density (see ¶ 3.1). Depending on the desired application, the correct conversion relationship should be applied.

NOTE 3: The conversion between resistivity and dopant density compiled by Irvin[7] is compared with this conversion (see Related Information 1). In this compilation, Irvin used the term 'impurity concentration' instead of the term 'dopant density.'

2.3 The self-consistency of the dopant density conversions (resistivity to dopant density and dopant density to resistivity) (see ¶ 7.3.1) is within 3% for boron from 0.0001 to 10,000 Ω·cm, (10^{12} to 10^{21} cm^{-3}) and within 4.5% for phosphorus from 0.0002 to 4000 Ω·cm (10^{12} to 5×10^{20} cm^{-3}). This error increases rapidly if the phosphorus conversions are used for densities above 5×10^{20} cm^{-3}.

2.4 The self-consistency of the carrier density conversions (resistivity to carrier density and carrier density to resistivity) is of similar magnitude.[3]

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3 Limitations

3.1 *Carrier Density* — Attempts to derive carrier density values from resistivity values by using conversions for dopant density are subject to error. While dopant density and carrier density values are expected to be nearly the same at 23°C 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 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. For derivation of carrier density from resistivity, use the appropriate relationship from § 7.4.

3.2 *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.

[7] Irvin, J. C. "Resistivity of Bulk Silicon and of Diffused Layers in Silicon." *Bell System Technical Journal*, Volume 41 (1962): pp. 387–410.

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3.3 *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 ($<10^{17}$ 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 causes different resistivities to be measured for the same dopant density. In this range the differences in resistivities are 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 ($>10^{19}$ cm^{-3}), the formation of complexes involving dopant atoms, lattice defects, and other impurities may lead to a modification in the number of charge carriers. The extent of this effect depends on 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.

3.4 *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.

NOTE 4: 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.[8] A semiconductor that exhibits compensation is said to be 'compensated.'

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

NOTE 5: It is possible to obtain dopant density values from resistivity values that were not measured at 23°C by using SEMI MF84 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 SEMI MF84 to obtain the resistivity at a temperature other than 23°C.

3.6 *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.

3.7 *Heavily Arsenic-Doped Silicon* — The relation given for heavily arsenic-doped silicon must not be used for densities outside the stated range because the equation diverges rapidly from realistic values of calculated resistivity. This is in contrast to the equations for boron and phosphorus, for which extrapolations are shown, although with unknown accuracy. This relation is stated for dopant density and resistivity but the density scale was obtained from Hall effect measurements, and thus has the same limitation as the conversion for heavily phosphorus-doped silicon (see ¶¶ 3.1 and 3.3). Unlike the samples used for the boron and phosphorus data base, which were Czochralski doped bulk silicon wafers, the samples used by Fair and Tsai[6] were arsenic diffusions into bulk silicon. However, the Fair and Tsai conversion for arsenic is supported by other studies on arsenic-diffused and arsenic-implanted specimens.[9,10,11,12] For the slightly reduced density range 2×10^{19} cm^{-3} to 10^{20} cm^{-3}, Fair and Tsai show that their arsenic conversion relation agrees with Irvin's conversion relation for *n*-type samples, which is discussed in Related Information 1.

[8] Blakemore, J. S. *Semiconductor Statistics*, Dover Publications, New York, 1987, § 3.3.

[9] Furukawa, Y. "Impurity Effect Upon Mobility in Heavily Doped Silicon." *Journal of the Physical Society of Japan*, Volume 16 (1961): p. 577.

[10] Murota, J., Arai, E., Kobayashi, K., and Kudo, K. "Relationship Between Total Arsenic and Electrically Active Arsenic Concentrations in Silicon Produced by the Diffusion Process." *Journal of Applied Physics*, Volume 50 (1979): p. 804.

[11] Matsumoto, S., Niimi, T., Murota, J., and Arai, E. "Carrier Concentration and Hall Mobility in Heavily Arsenic-Diffused Silicon." *Journal Electrochemical Society*, Volume 127 (1980): p. 1650.

[12] Masetti, G., Severi, M., and Solmi, S. "Modeling of Carrier Mobility Against Carrier Concentration in Arsenic-, Phosphorus-, and Boron-Doped Silicon." *IEEE Transactions on Electron Devices*, ED-30 (1983): p. 764.

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