Resistivity-Dopant Density Relationship for Phosphorus-Doped Silicon

This paper [1], together with its companion [2], *Resistivity-Dopant Density Relationship for Boron-Doped Silicon,* documents the work done from about 1975 to 1980 to obtain a more accurate relationship between the resistivity and dopant density of silicon. The conversion between these two material properties is widely used in the semiconductor industry since silicon is the primary material which has powered the information age. A conversion is needed because many applications involve relating resistivity, which is known or can be readily measured, to dopant density, the desired quantity which is very difficult to measure directly. To model the processing of an integrated circuit, the conversion is used to calculate the surface carrier concentration of a diffused layer from the sheet resistance—junction depth product and to determine the dopant density profile from incremental sheet resistance measurements. Significant error in the results of these measurements occurs when incorrect expressions are used to relate resistivity and dopant density.

The work was initiated because of disagreements between measured values and those calculated using the existing relationships. Numerous measurement methods were used for the redetermination of the relationship for silicon doped with boron (p-type) or phosphorus (n-type). Results were obtained from more than 77 wafers, mostly donated by industry, that spanned the dopant density range from 10^{13} cm^{-3} to 10^{20} cm^{-3}. For dopant densities less than 10^{18} cm^{-3}, resistivity and junction capacitance-voltage measurements were made on processed wafers. For more heavily doped material, data were obtained from Hall effect and resistivity measurements on samples cut from bulk silicon wafers. These primary methods were supplemented for phosphorus-doped material by neutron activation analysis and a photometric technique [3], and for boron-doped material by the nuclear track technique [4]. Analytical curves were fitted to the resistivity-dopant density product as a function of resistivity and dopant density for temperatures of both 23 °C and 27 °C. Similar curves were obtained for the calculated carrier mobility as a function of resistivity and carrier density.

A comprehensive report on the work, including tables of the data and curve fitting details, was published as an NBS Special Publication [5]. For phosphorus-doped silicon, the results of this work differed by 5 % to 15 % from the then commonly used curve. For boron-doped silicon the results differed significantly from the p-type curve in use at the time. A maximum deviation of 45 % occurred at a boron density of 5×10^{17} cm^{-3}. Because of the large differences, ASTM Committee F-1 decided that the semiconductor industry needed a recommended conversion. The results of this work formed the basis of a new ASTM Standard Practice [6] for the conversion between resistivity and dopant density. It remains the accepted conversion to use, and either the original publications or the ASTM document are referenced in many papers and textbooks, as well as in five other ASTM measurement standards. The graph of dopant density vs. resistivity in Fig. 1, reproduced from the ASTM standard, is the reference chart normally used by workers in the field. This chart and the associated analytical fits are commonly referred to as the Thurber curves.

W. Robert Thurber was born in Butte, Nebraska, on July 10, 1938. He received an A. B. degree in physics from Nebraska Wesleyan University in 1960 and an M. S. degree in physics from the University of Maryland in 1963. He has been with NIST since 1962 and is presently an experimental physicist in the Semiconductor Electronics Division.

He has had broad experience in the measurement of the electrical and optical properties of semiconductors. Past projects include the electrical properties of gold-doped silicon, infrared absorption due to oxygen in silicon and germanium, and microelectronic test structures for the measurement of parameters important for integrated circuit processing. The characterization of impurities in semiconductors using deep level transient spectroscopy (DLTS) is another area of expertise. A novel method to detect nonexponential capacitance transients was developed. Thurber was heavily involved in writing an ASTM method on transient capacitance measurements and was in charge of a round robin to verify the method.

Thurber has also worked on the high-priority project to investigate the problems of infrared detectors used on the NOAA GOES satellites. An ac impedance method was developed for measuring the very high resistivity of silicon ingots used for detector applications. He also did research on the photo response in p-type silicon containing oxygen. Recently, he assembled a Hall effect and resistivity measurement system which he is using to characterize GaAs samples for an upcoming inter-

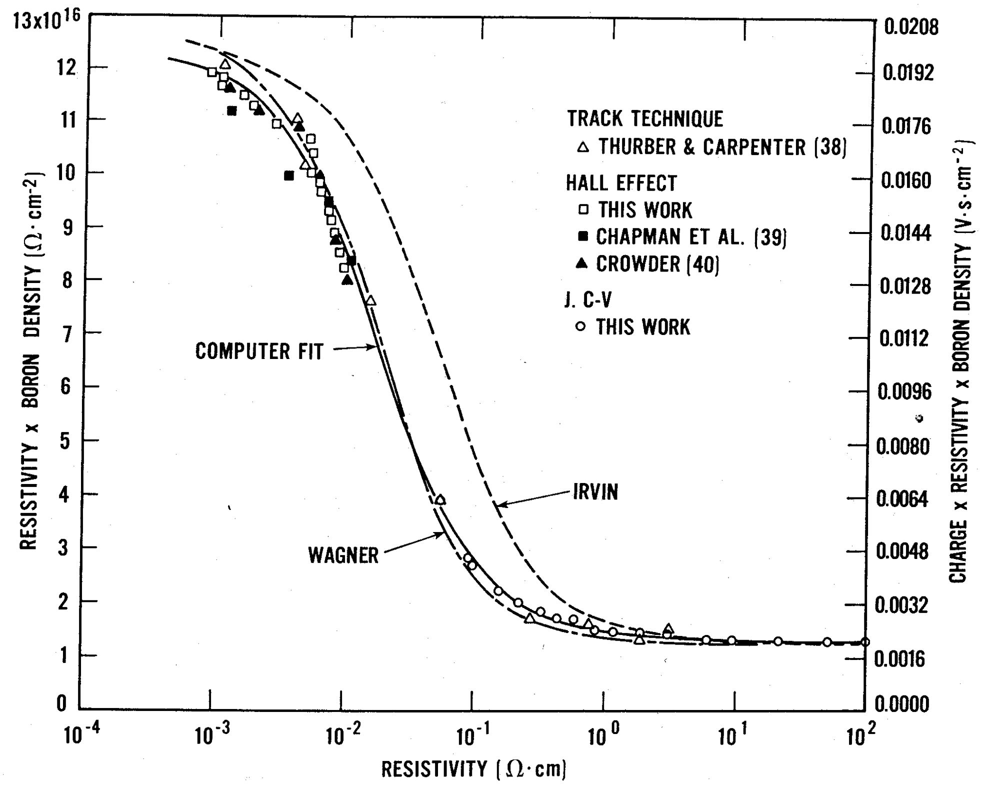

Fig. 1. One of the two "Thurber Curves"; there is a companion curve for phosphorous-doped silicon. Plotted is resistivity-dopant density product as a function of resistivity at 300 K for boron-doped silicon. The junction capacitance voltage and Hall effect measurements are compared with the published work of Thurber and Carpenter [4] and other values in the literature. The solid curve is an analytical fit to portions of these data. Values of the product of charge, resistivity, and boron density are on the right ordinate.

national Hall effect round robin which NIST will coordinate. He helped put together a tutorial Hall effect web page which invites viewer comments and will also be used to report results of the round robin.

Prepared by W. R. Thurber.

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