Evaluation of the Surface Concentration of Diffused Layers in Silicon

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A method for determining the surface concentration of diffused impurity layers in semiconductors is described. It is shown that the surface concentration may be evaluated if the sheet resistivity of the layer, junction depth, impurity distribution across the layer, background resistivity and the majority carrier mobility are known. The calculations have been made for several typical impurity distributions in silicon.

I. INTRODUCTION

Recently the investigation of the diffusion of electrically active impurities in semiconducting materials has become important because of the use of diffusion technology in the fabrication of semiconductor devices. A diffused layer is characterized by the impurity distribution; its mathematical form is obtained by solution of the diffusion equation with the appropriate boundary conditions. When the distribution is known, two of the following parameters may be chosen to describe the layer completely: diffusion coefficient — time product, surface concentration, total number of diffused atoms and concentration at a given depth. Of these quantities, only the depth is easily measured. Another readily measured quantity of the layer is its sheet resistivity. But, from the point of view of the device designer, the junction depth and surface concentration are the most important quantities. The present paper shows how the surface concentration of a diffused layer may be obtained from the sheet resistivity and junction depth if the impurity distribution, the majority carrier mobilities, and the resistivity of the silicon are known. The necessary evaluations are given here for the case of diffusion of Group III and V elements into uniformly doped silicon of the opposite conductivity type.

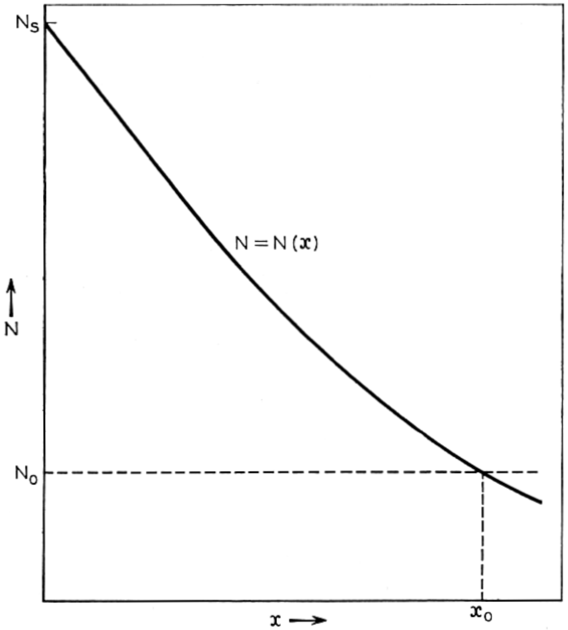

Fig. 1 — Assumed impurity distribution, with N_0 representing the impurity concentration of the original material.

II. METHOD

Fig. 1 shows an assumed impurity distribution, with N_0 representing the impurity concentration of the original material. A *p-n* junction is formed at a depth x_0 where the impurity concentration of the diffusant equals N_0. The depth of this junction x_0 can be obtained by one of several techniques.[1, 2] Thus a concentration at a given depth is known. If all impurities are ionized, the following relation holds for the average conductivity $\bar{\sigma}$ of an impurity layer of the thickness x_0,

$$\bar{\sigma} = \frac{1}{\rho_s x_0} = \frac{1}{x_0} q \int_0^{x_0} \mu(n)[N(x) - N_0] \, dx, \tag{1}$$

with the conditions

$$N(x_0) = N_0, \tag{2}$$

and $N(0) = N_s$ where N_s is the surface concentration. The quantity ρ_s can be obtained by a four-point probe measurement[3] on the surface. In silicon the saturation currents are so low that the junction may be regarded as an open circuit, so that the measured sheet resistivity is

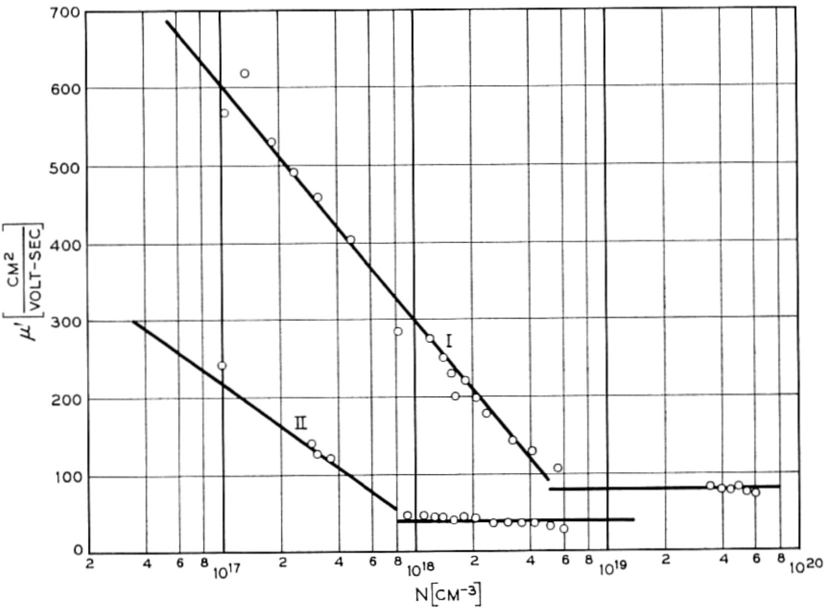

Fig. 2 — Effective mobility $\mu'(N)$ as determined by radioactive techniques for donor (curve I), and acceptor (curve II) elements in silicon.

essentially that of the layer alone. $N(x)$ represents the impurity density as a function of the distance x from the surface, and μ is the majority carrier conductivity mobility, which depends on the ionized impurity density n. Since only a fraction of the impurity atoms are ionized, particularly in heavily doped silicon, an appropriate correction must be made. This fact may be taken into account more directly by introducing and effective mobility $\mu'(N)$ defined by:

$$\mu' = 1/q\rho N, \tag{3}$$

where q is the magnitude of the electron charge and ρ the resistivity. The effective mobility $\mu'(N)$ has been determined by radioactive techniques for different impurity elements[4] and is shown in Fig. 2.

The results of these measurements can be described approximately by an analytic expression of the form

$$\begin{aligned} \mu_n' &= 300\,(19 - \log N) \text{ for } 10^{16} < N < 5.10^{18} \text{ cm}^{-3} \\ \mu_n' &= 80 \qquad\qquad\qquad\quad \text{for } 5.10^{18} < N < 10^{20} \text{ cm}^{-3} \end{aligned} \tag{4a}$$

for electrons, and

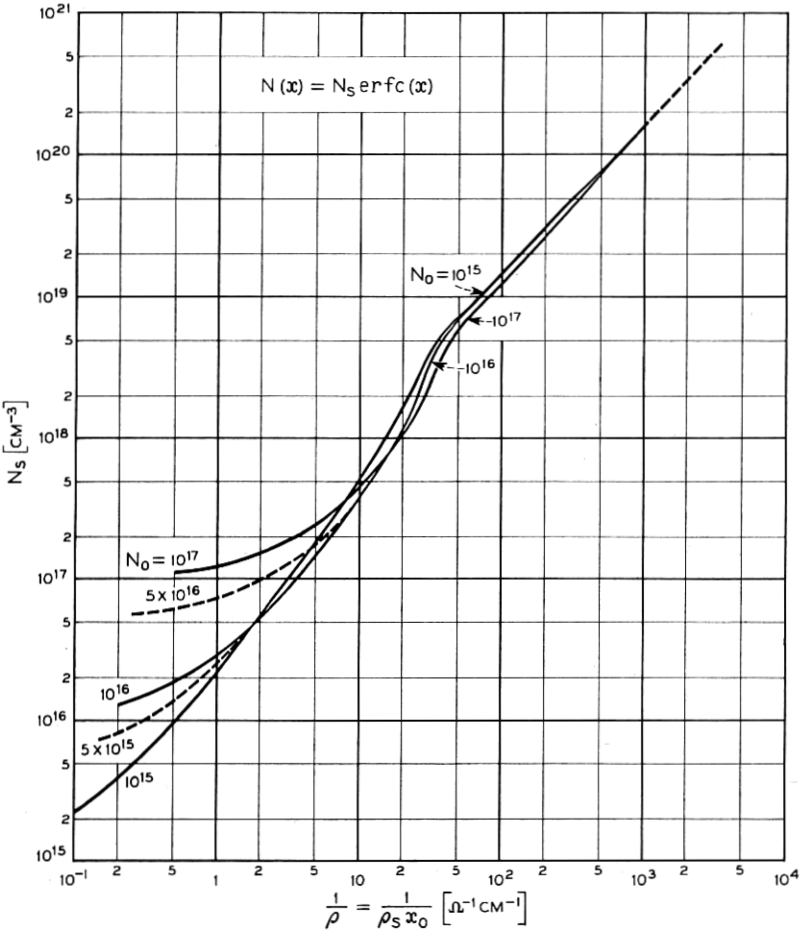

Fig. 3 — Surface concentration N_s versus conductivity $(1/\rho)$ for an n-type layer; complementary error function distribution.

$$\begin{aligned} \mu_p' &= 180\ (18.2 - \log N) && \text{for } 10^{16} < N < 8.10^{17}\ \text{cm}^{-3} \\ \mu_p' &= 40 && \text{for } 8.10^{17} < N < 10^{20}\ \text{cm}^{-3} \end{aligned} \tag{4b}$$

for holes.

The hole mobility μ_p' was measured only to 6.10^{18} cm^{-3} but its decrease for higher concentrations is so small that the assumption of a constant mobility up to 10^{20} cm^{-3} is justified. With a specified distribution, the

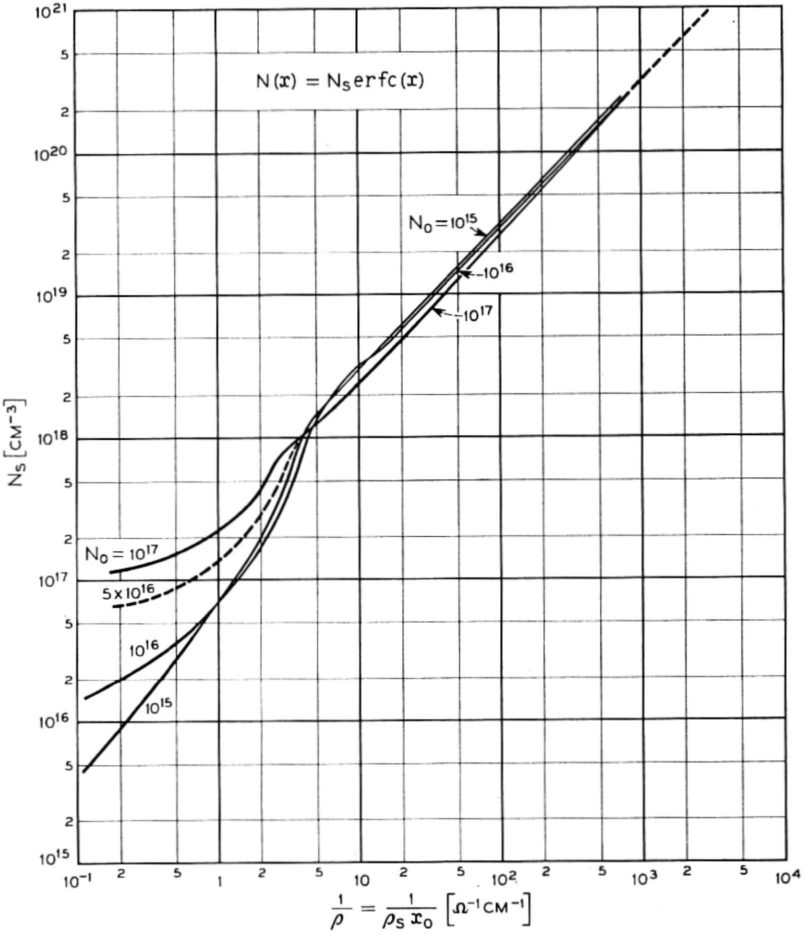

Fig. 4 — Surface concentration N_s versus conductivity $(1/\bar{\rho})$ for a p-type layer; complementary error function distribution.

surface concentration, N_s, can be evaluated as a function of $1/\rho_s x_0$ from (1), (2) and (4).

III. RESULTS

The calculations have been carried out for several distinct distributions which occur in different diffusion processes.

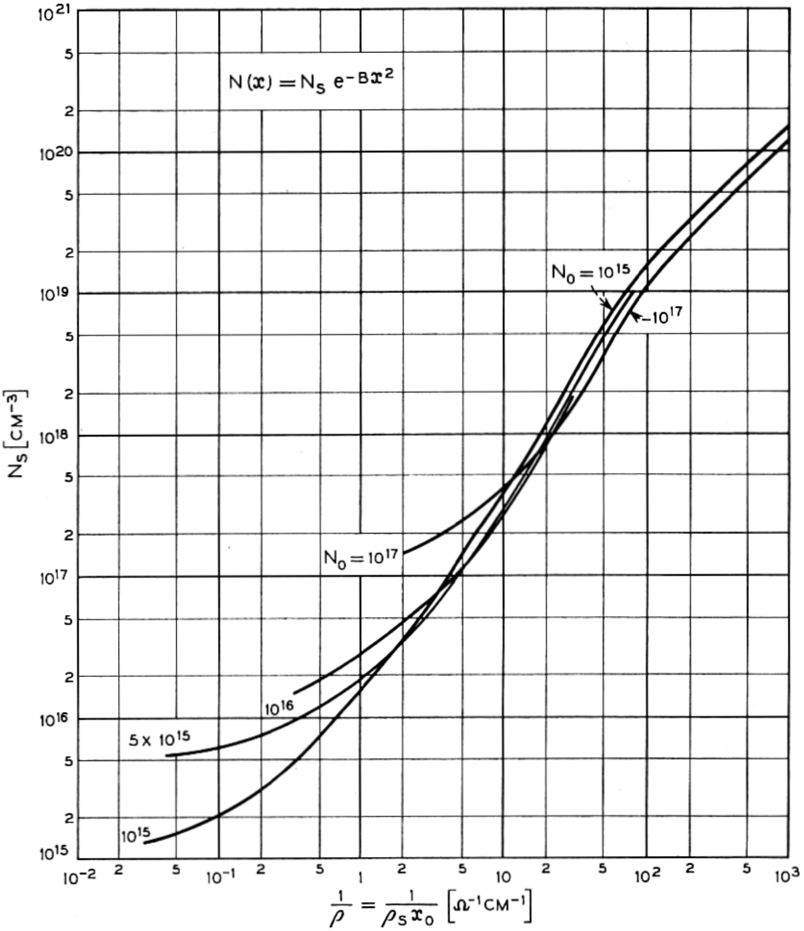

Fig. 5 — Surface concentration N_s versus conductivity for an n-type layer; Gaussian distribution.

Case I:

The maintenance of a constant impurity concentration at the surface during the diffusion leads to the complementary error function solution of the diffusion equation, that is

$$N(x) = N_s \operatorname{erfc} (x/2\sqrt{Dt}).$$

The results are plotted in Figs. 3 and 4 for an n-type and a p-type layer

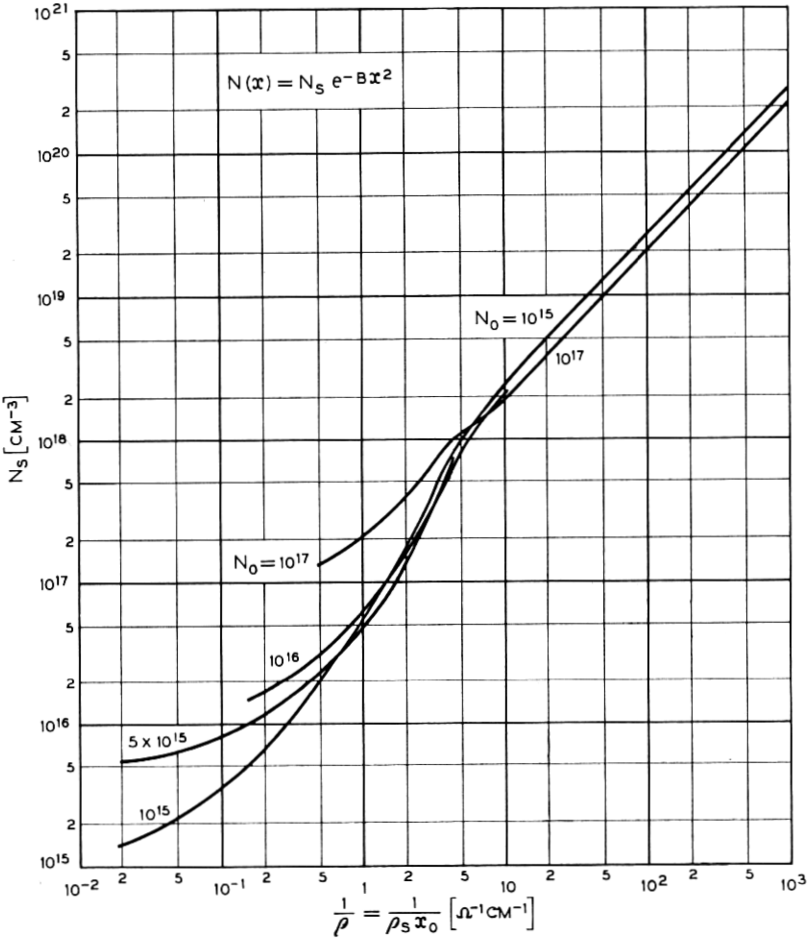

Fig. 6 — Surface concentration N_s versus conductivity for a p-type layer; Gaussian distribution.

respectively. N_s is plotted versus $1/\rho_s x_0$ with background concentrations N_0 as a parameter.

Case II:

If the initial impurity distribution is represented by a δ-function, one obtains after diffusion a Gaussian distribution

$$N(x) = N_s \exp(-x^2/4Dt).$$

Figs. 5 and 6 show corresponding plots for n- and p-type layers.

Case III:

If a constant surface concentration is maintained and the silicon is simultaneously evaporating at a constant rate, v, the resulting impurity distribution is exponential[5]

$$N(x) = N_s \exp(-vx/D).$$

Figs. 7 and 8 give the corresponding plots.

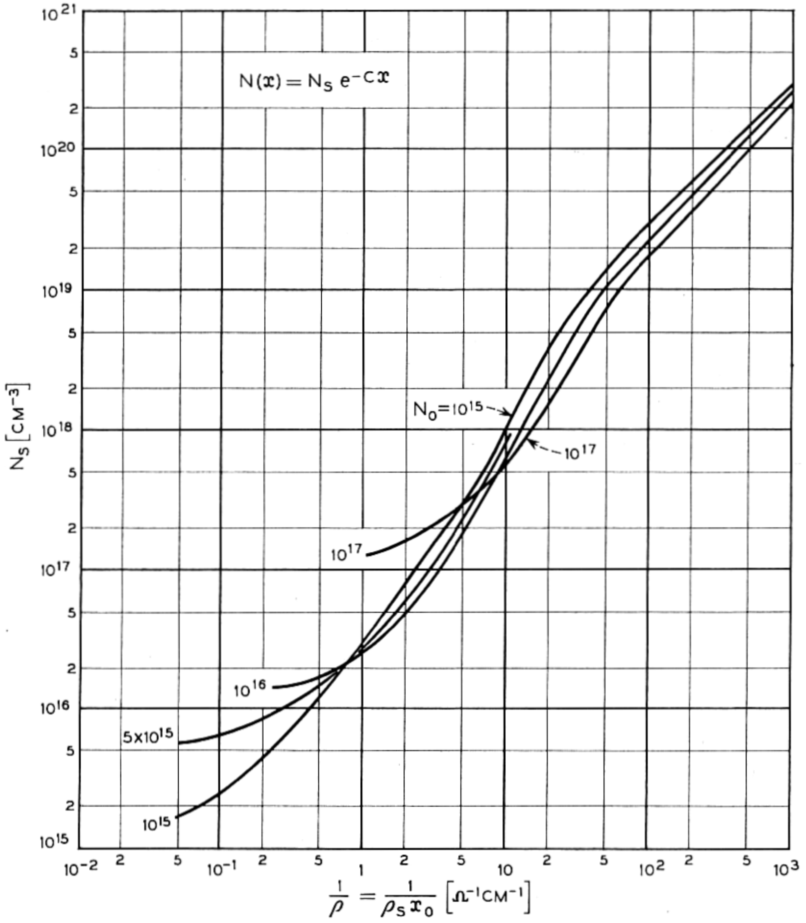

Fig. 7 — Surface concentration N_s versus conductivity for an n-type layer; exponential distribution.

Case IV:

Finally, curves for a linear impurity distribution

$$N(x) = N_s - (N_s - N_0)x/x_0$$

are given in Figs. 9 and 10.

It should be pointed out that the effective mobilities μ' are different for elements with different ionization energies. However, the ionization

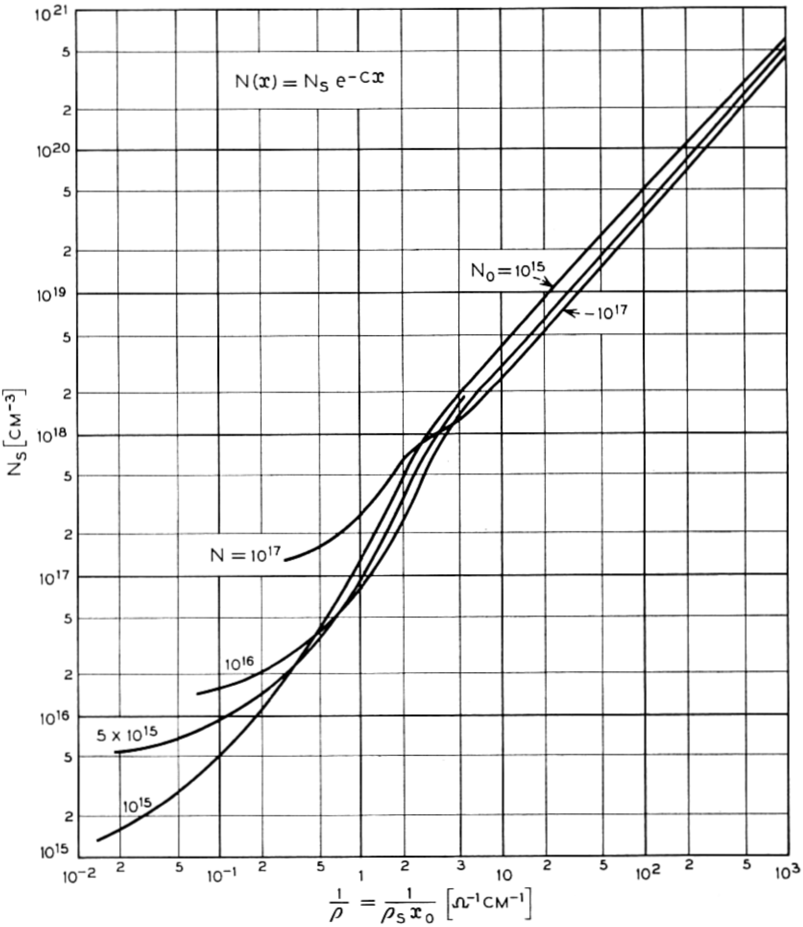

Fig. 8 — Surface concentration N_s versus conductivity for a p-type layer; exponential distribution.

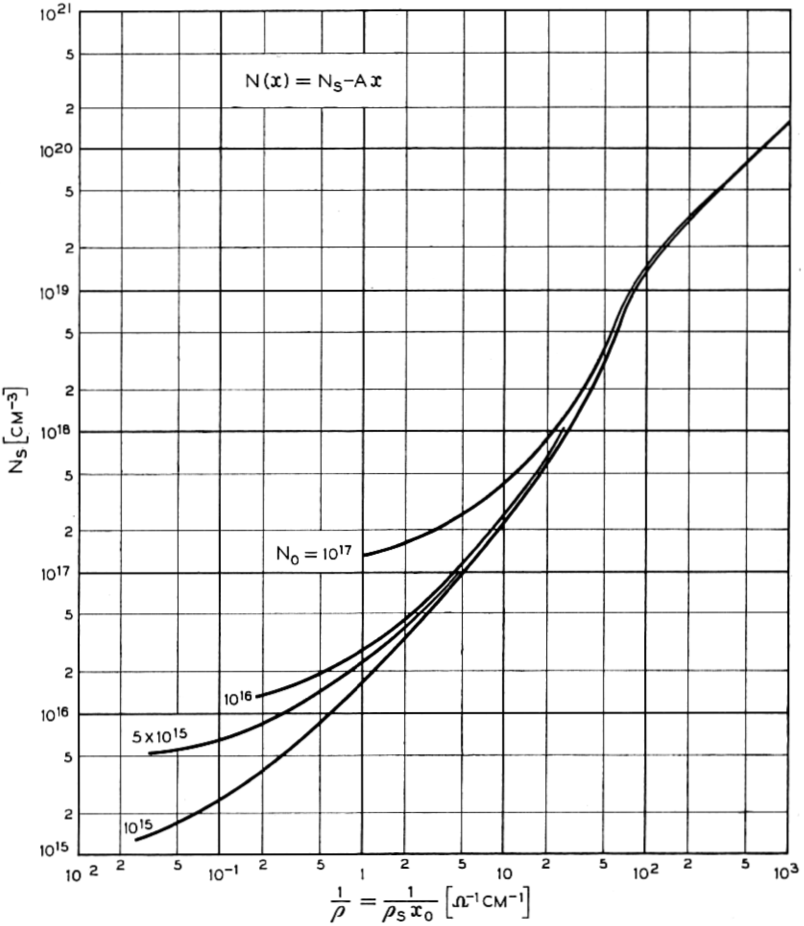

Fig. 9 — Surface concentration N_s versus conductivity for an n-type layer; linear distribution.

energies of all commonly used Group V donor elements differ from each other only slightly. Therefore, (4a) is approximately true for all these elements. The differences in the ionization energies of the Group III acceptor elements are also small, with the exception of indium. Hence, (4b) is good for boron, aluminum and gallium, but is not valid for indium. Deviations of N_s somewhat less than a factor of two may be expected in this case.

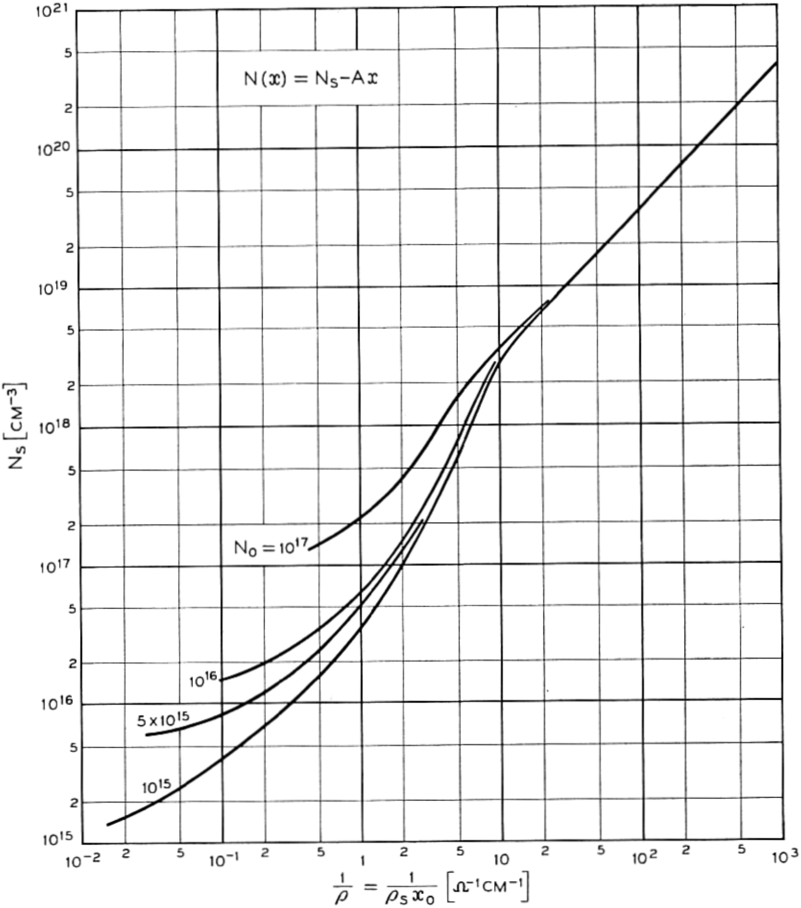

Fig. 10 — Surface concentration N_s versus conductivity for a p-type layer linear distribution.

IV. ACKNOWLEDGMENT

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REFERENCES

1. Bond, W. L. and Smits, F. M., The Use of an Interference Microscope for Measurement of Extremely Thin Layers, B.S.T.J., **35,** September, 1956, p. 1209.

2. Fuller, C. S. and Ditzenberger, J. A., Diffusion of Donor and Acceptor Elements in Silicon, J. Appl. Phys., **27,** May, 1956, p. 544.
3. Valdes, L. B., Resistivity Measurements on Germanium for Transistors, Proc. of I.R.E., **42,** February, 1954, p. 420; Smits, F. M., this issue, p. 711.
4. Backenstoss, G., Conductivity Mobilities of Electrons and Holes in Heavily Doped Silicon, Phys. Rev., **108,** Dec. 15, 1957, p. 416.
5. Smits, F. M., Miller, R. C., and Batdorf, R. L., Surface Effects on the Diffusion of Impurities in Semiconductors, in *International Symposium on Semiconductors and Phosphors (1956)*, F. Viweg, Braunschweig, in press.