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ERROR ESTIMATE FOR THERMAL RESISTANCE MEASUREMENTS ON UNCOATED Si MICROWAVE TRANSISTORS AS RESULT OF TEMPERATURE GRADIENTS

HERBERT L. METTE

AUGUST 1972

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ABSTRACT

A vertical temperature gradient's effect upon temperature radiation emitted from partially metalized silicon (Si) transistor substrates has been investigated. The theoretical error of a surface temperature reading, obtained with the IR scanning method, has been estimated. This numerical analysis indicates that significant temperature errors occur only for n-resistivities above 0.02 Ω .cm and for p-resistivities above 0.05 Ω .cm; consequently, no surface coating with paint is necessary for lower resistive substrates.

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ERROR ESTIMATE FOR THERMAL RESISTANCE MEASUREMENTS ON UNCOATED Si MICROWAVE TRANSISTORS AS RESULT OF TEMPERATURE GRADIENTS

1. INTRODUCTION

An important characteristic for the usefulness of microwave power transistors is the maximum temperature rise, ΔT_{Max}, that occurs at any one point of the transistor surface, if the total power W, is dissipated in the transistor. The quantity $\theta = \Delta T_{Max}/W$ is referred to as the "thermal resistance" of the transistor.* Measurement of the power dissipation, W, in a transistor usually presents no problems, but considerable controversy exists regarding the method used to measure the temperature of surface hot spots. It is agreed that some technique involving scanning of the surface and measuring the radiation emitted from each point with an infrared sensitive microscope** is appropriate. Disagreement exists, however, as to exactly how the surface of the transistors should be treated for this measurement and, in particular, whether it should be left uncoated or coated with black paint. The following discussion will give the pros and cons of such a procedure and establish criteria as to when transistor surfaces should be coated.

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*This designation is theoretically not quite correct. Thermal resistance is usually defined as the temperature difference, ΔT, between two interfaces, divided by the heat flow through both interfaces. In transistors, however, the bonded interface of the silicon (Si) chip against the heat sink is usually designated as one of the interfaces; the choice of the transistor top surface as an interface is problematic, since heat is actually not produced at the surface but in the junction some distance from the surface. Measuring the surface temperature for thermal resistance determinations will, therefore, introduce a small but measurable error into the calculation, because the heat loss through radiation makes the surface temperature appear lower than the junction temperature. Also, the temperature over the surface is not uniform, and the true thermal resistance of the transistor would have to be the integral of the thermal resistivities over the entire surface. When considering power transistors, however, one is interested in the highest temperature rise, ΔT_{Max}, which can be measured in any one spot when the total power dissipation in the transistor is W; we shall, therefore, follow the general practice of calling $\Delta T_{Max}/W$ the thermal resistance of the transistor.

**Example: Sierra/Philco "High Speed Thermal Microplotter Model 705B."

2. ARGUMENTS FOR OR AGAINST PAINTING THE TRANSISTOR SURFACE BLACK

The reasons usually cited for coating the transistor surface black are as follows:

a. The indium antiomonide (InSb) infrared scanner used to measure the heat radiation is most sensitive in the region between 3 and 6 μm. Pure Si is transparent above 1.1 μm. Therefore, one does not measure the true temperature of the transistor surface, but rather the temperature that is influenced by the bonded heat sink underneath. Black paint, however, will indicate the precise temperature of the surface.

b. The emissivity of black paint is many times higher than that of the metalized part of the surface. Temperature measurement of painted surfaces is, therefore, more precise than unpainted surfaces.

c. The hottest part of the transistor is under the metalized aluminum-emitter contacts. Because of the low emissivity of aluminum and the low resolution of the thermoscanner, the radiation from these hot spots is averaged with a low weighting factor against the colder regions of the Si surface.

The arguments against painting the transistor surface black are as follows:

a. This is a destructive method, and the transistor is lost after testing.

b. Since the paint layers employed are approximately 2 mils thick, the surface contours of the transistor are not discernible through the microscope; identification of the sites of the transistor surface hot spots is difficult if not impossible.

c. The coating of the transistor surface with black paint places unknown quantities of impure ions over the passivated layer which may change the transistor's characteristics.

d. Since paint has a high dielectric constant (typically around 3) in the microwave region, a dielectric layer, several mils thick, may easily detune the transistor measuring circuit and cause abnormally high power dissipation.

e. The electrical conductivity of paint decreases exponentially with temperature and may reach the point where it becomes self-heating and has its own hot spots.

f. Due to the low thermal conductivity of paint, a substantial temperature gradient can occur across this layer, especially when it is forced air cooled and result in misreading the temperature of the surface.

3. THEORETICAL ESTIMATES FOR ERROR ON UNPAINTED SURFACES

It is quite clear from this argument that measurements on unpainted surfaces are to be preferred, if the error produced in this manner can be tolerated. The following will, however, estimate the size of this error for a number of practical configurations. Basically, this error depends on the following quantities: degree of metalization, emissivity of the metalized area, thickness and resistivity of the Si substrate, and the temperature gradient across the sample. The following will consider the effect of each of these quantities.

Consider a slab of Si of the thickness d (Fig. 1). A fraction of the surface, called a, is metalized. Since the spot size of the scanner is typically 2 mil square in area, the radiation reaching the microscope is always a mixture of radiation coming from the metal and from the Si part of the surface. If Si is of high resistivity (ρ), then its absorption coefficient, α, is low, and a portion of the radiation from the Si actually comes from deeper Si layers[1] or even the heat sink. This results in calibration errors, if a vertical temperature gradient exists in the Si and radiation from the colder bulk of the samples mixes with the radiation coming from the hotter regions near the surface. The problem of determining the error in surface temperature measurements by the scanning method is now equivalent to finding the amount of total radiation coming from the colder inside of the wafer in relation to the total radiation coming from the entire Si wafer and to finding the error in temperature reading that this difference in radiation produces in the scanner for a given S, a, and α, when the surface temperature is T and a vertical temperature gradient, dT/dx, exists. Since we are only discussing microwave power transistors, we may assume that the emitter metalization strips are spaced several μm apart, and no lateral gradient exists along the surface. In quantitative terms, the total radiation reaching the microscope from the metalized and unmetalized region can now be expressed by

$$I = \{a\, S_{Met} + (1-a)\, S_{Si}\}\ R(T,\Delta\lambda) \quad , \qquad (1)$$

where S_{Met} and S_{Si} are the emissivities of the metal and Si areas, $R(T,\Delta\lambda)$ is the radiation function corresponding to the black body radiation falling within the photoconductive sensitivity range (3-6 μm) of the IR detector. As pointed out above, S_{Si} is not a surface but a bulk property and is dependent on the absorption coefficient and temperature gradient within the Si. Some concern exists with regard to the protective oxide over the Si, but since its thickness is typically less than one quarter of the IR wavelength, it, therefore, does not interact with radiation coming from the Si or metal films or emit radiation on its own. We may for the purpose of this calculation ignore the existence of such films.

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[1] R. Gardon, "The Emission of Radiation by Transparent Materials," Henry Blau and Heinz Fischer, Editors, Radiative Transfer from Solid Materials (MacMillan & Co, New York, 1962).

In order to estimate S_{Si} as a function of the absorption coefficient, we assume initially that no vertical temperature gradient exists, restricting ourselves to the case of highly doped materials, i.e., $1/\alpha < d$, where only IR radiation from the bulk Si and almost none of the back interface can reach the front. The radiation, r, reaching the surface from a layer, dx, at the depth x of the sample is then given by:*

$$r dx = \alpha e^{-\alpha x} R(T, \Delta\lambda) dx \qquad (2)$$

Since the entire wafer is kept at a uniform temperature, R is independent of x. Because of the assumption $1/\alpha < d$, we can extend the integration limit to ∞ and obtain

$$\int_0^\infty r dx = R(T, \Delta\lambda) \qquad (3)$$

The amount of radiation capable of leaving the surface is smaller than the radiation reaching the surface because of reflection losses due to the high refractive index of Si ($n = 3.43$) in the wavelength range under consideration. This reflection loss is given by $(n-1)^2/(n+1)^2$ and amounts, in our case, to 30%. It follows that Si without a temperature gradient has an emissivity of

$$S_{Si,grad = 0} = 0.7 \qquad (4)$$

regardless of its absorption coefficient, α, within the limits of approximation discussed above.

We shall now consider the case where the temperature, T, decreases from the surface temperature, T_s, at a rate dT/dx. R, in this case, becomes a function of x, but for small temperature gradients, we can approximate $R = R_{T_s} - \Delta R$, where ΔR follows from Stefan-Boltzmann's law, $R = \sigma T^4$ (with σ = Stefan-Boltzmann constant) as

$$\frac{\Delta R}{R} = 4 \frac{\Delta T}{T} = 4 \frac{\Delta T}{\Delta x} \frac{x}{T_s} \qquad (5)$$

Substituting Equation (5) into Equation (2), we obtain the following expression for the total amount of radiation reaching the surface from the bulk where a temperature gradient dT/dx exists:

$$\int_0^\infty r_{grad \neq 0} dx = \alpha \int_0^\infty e^{-\alpha x} \left[1 - 4 \frac{\Delta T}{\Delta x} \frac{x}{T_s} \right] R(T, \Delta\lambda) dx \qquad (6)$$

---

*We neglect here, and hereafter, all reabsorption and reemission of radiation in the transparent region of the Si.

Substituting Equation (5) and integrating the above, the equation becomes:

$$_{0}\int^{d} r_{grad \neq 0}\, dx = \left(1 - 4 \frac{\Delta T}{\Delta x} \frac{1}{T_s \cdot \alpha}\right) R(T, \Delta \lambda) \qquad (7)$$

We can now calculate the emissivity of Si with a surface temperature T_s (i.e., the fraction of radiation that can leave the surface from a sample having a temperature gradient, dT/dx, in relation to the total amount of radiation that would be generated in the Si if no temperature gradient exists), obtaining:

$$S_{Si, grad \neq 0} = 0.7 \left(1 - 4 \frac{\Delta T}{\Delta x} \frac{1}{T_s \cdot \alpha}\right) \qquad (8)$$

4. TYPICAL ERRORS FOR PARTIALLY METALIZED SURFACES

We are now able to estimate the error in radiation reading from a Si wafer that is caused by the presence of a vertical temperature gradient from

$$\text{Error} = \frac{I_{grad=0} - I_{grad \neq 0}}{I_{grad=0}}$$, where $I_{grad=0}$ and $I_{grad \neq 0}$ represents the

total radiation according to Equation (1) for a Si wafer with or without a gradient. Substituting Equations (4) and (8) into Equation (1), we obtain:

$$\text{Error} = \frac{(1-a)\,(S_{Si, grad \neq 0} - S_{Si, grad=0})}{a\ S_{Met} + (1-a)\ S_{Si, grad \neq 0}} = \frac{4 \frac{\Delta T}{\Delta x} - \frac{1}{T_s \cdot \alpha}}{\frac{a}{0.7\,(1-\alpha)}\ S_{Si} + 1} \qquad (9)$$

We now calculate this error for the following parameters that are typical for microwave transistors:

a = 1/2 (1/2 of the transistor surface is metalized)

S_{Met} = 0.1* (see Ref. 2)

T_s = 400°K

d = 100 μm

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*This value was chosen as an estimate between S = 1.1 for oxidized and S = 0.08 for highly polished Al.

[2] C. Hodgman, Handbook of Chemistry and Physics (Chemical Rubber Publishing Co., Cleveland, Ohio, 1951), 33rd Edition, pp. 2452-2453.

Figure 2 plots the error, computed from Equation (9), in radiation emitted from a Si surface for various Si materials having absorption coefficients, α = 125, 166, 250, 500, and 1000 cm^{-1} (corresponding[3,4] to n-resistivities of 0.014, 0.009, 0.007, 0.005, and 0.0025 Ω.cm) and temperature gradients of 1, 2, 3, 4, and 5 x 10^3 °C/cm (corresponding to temperature differences of ΔT = 10, 20, 30, 40, and 50°C across the 100 μm thick sample). In the most unfavorable case considered, i.e., for relatively pure (0.014 Ω.cm) Si substrates and large temperature differences of 50°C across the sample, the surface is at 127°C and the maximum radiation error measurement as a result of this gradient would be 35%. However, because of the non-linear radiation-temperature dependence of the measuring system, the actual temperature error is much lower. Taking a typical calibration curve for Si from a Sierra-Philco Microscanner, one obtains the temperature errors plotted in Fig. 3 as a function of temperature difference across the wafer for various resistivities. It is noticed that in this way a maximum temperature error of only 12.5% occurs as upper limit in the extremely unlikely case that the temperature difference is 50°C and the Si is n-type and of 0.014 Ω.cm resistivity (or p-type* of 0.05 Ω.cm resistivity). Most microwave transistors, however, have lower resistivities, and their temperature differences across the wafer** are most likely less than 50°C. The true error may be still smaller, since we have not taken into account the grating effect of the metalization. This occurs when the Si openings between the metalization fingers of the transistor are less than the wavelength of 3-6 μm of the IR scanner. The net effect of such diffraction grating effect would be to cause wider angular distribution of the radiation than from unmetalized Si.

5. CONCLUSIONS

The numerical estimate for the error in temperature readings of surface scanned Si transistors, illustrated for 100 μm thick substrates and 50% metalization, can easily be extended to other geometries and temperature gradients using Equations (1) and (8). It is clear from these examples that substantial errors in temperature readings with the thermoscanner method will only occur when the substrate resistivity becomes larger than 0.02 Ω.cm for n-type and approximately 0.05 Ω.cm for p-type. For lower resistivity materials, the potential errors in temperature readings for uncoated samples are more than offset by errors that could be introduced by the coating of the surfaces with black paint.

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*Absorption coefficients for heavily doped p-Si are not available but can be extrapolated from measurements at lower doping levels (Vavilov, August, 1960).[4]

**It should be noted that beryllia, which is frequently used as heat sink material for microwave transistors, has a similar thermal resistivity as Si and that, therefore, in the Si-beryllia composite structure a larger temperature drop will occur in the thicker beryllia heat sink than in the very thin Si.

[3] W. Spitzer and H. Y. Fan, "Infrared Absorption in n-type Silicon," Phys. Rev., Vol. 108, pp. 268-271, 1957.

[4] V. S. Vavilov, "The Absorption of Free Charge Carriers by Infrared Radiation in Silicon," Soviet Physics-Solid State, Vol. 2, No. 2, pp. 346-349, August 1960.

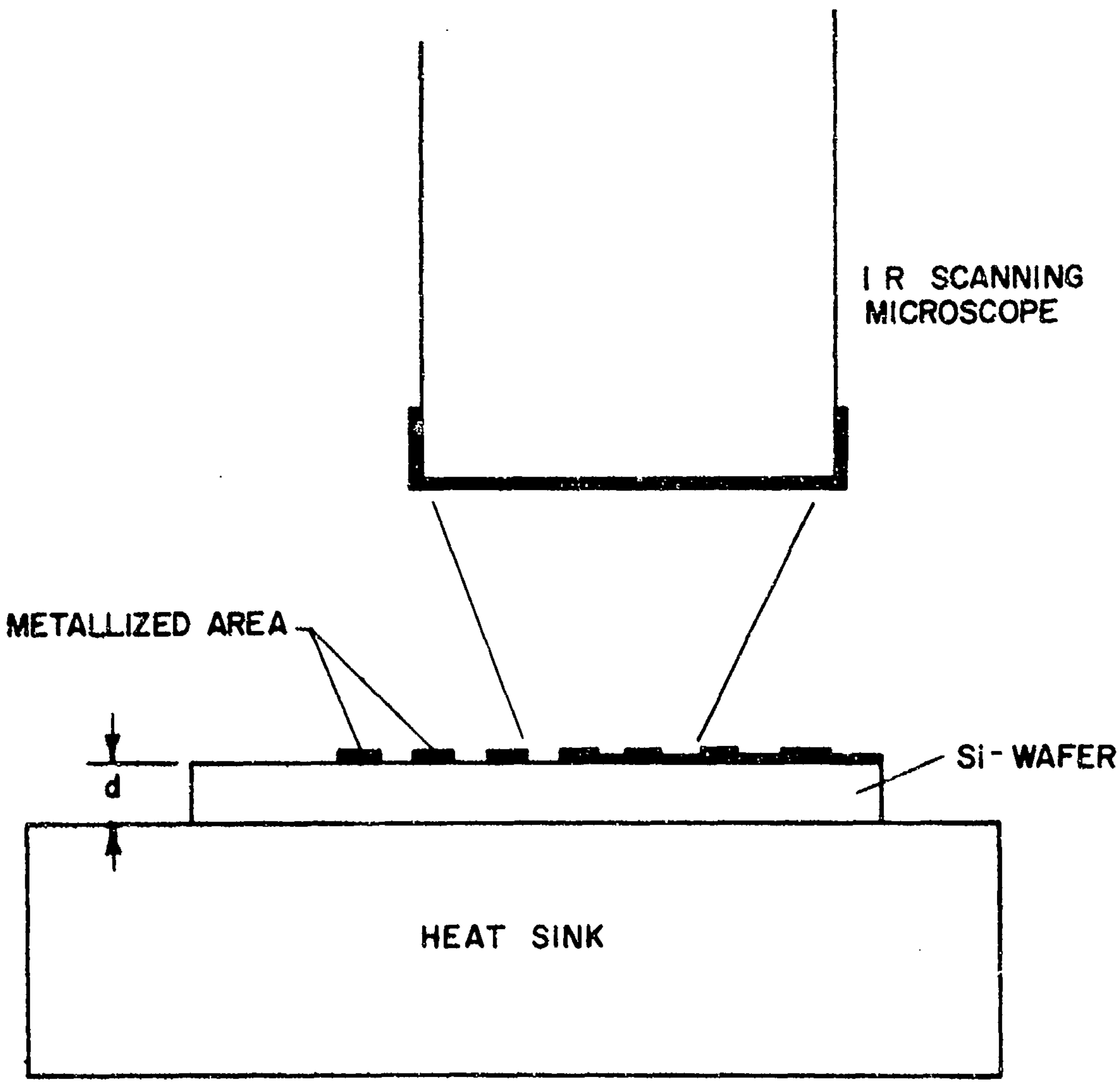

FIG. I. SCHEMATIC OF MEASURING ARRANGEMENT FOR SURFACE TEMPERATURE SCANNING

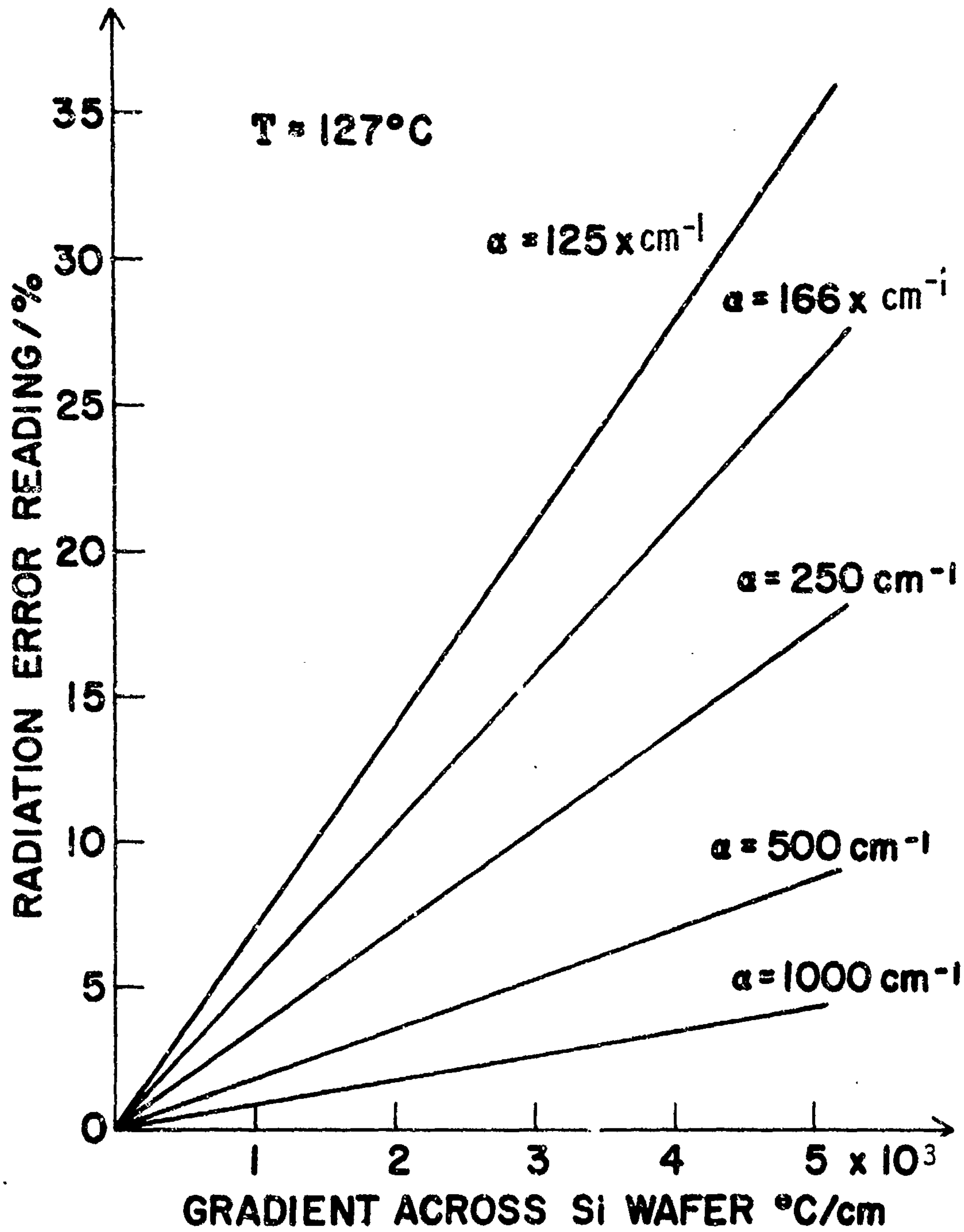

FIG. 2. LOWERING OF TEMPERATURE RADIATION EMITTED FROM Si SURFACE AS A RESULT OF VERTICAL TEMPERATURE GRADIENT FOR VARIOUS ABSORPTION CONSTANTS

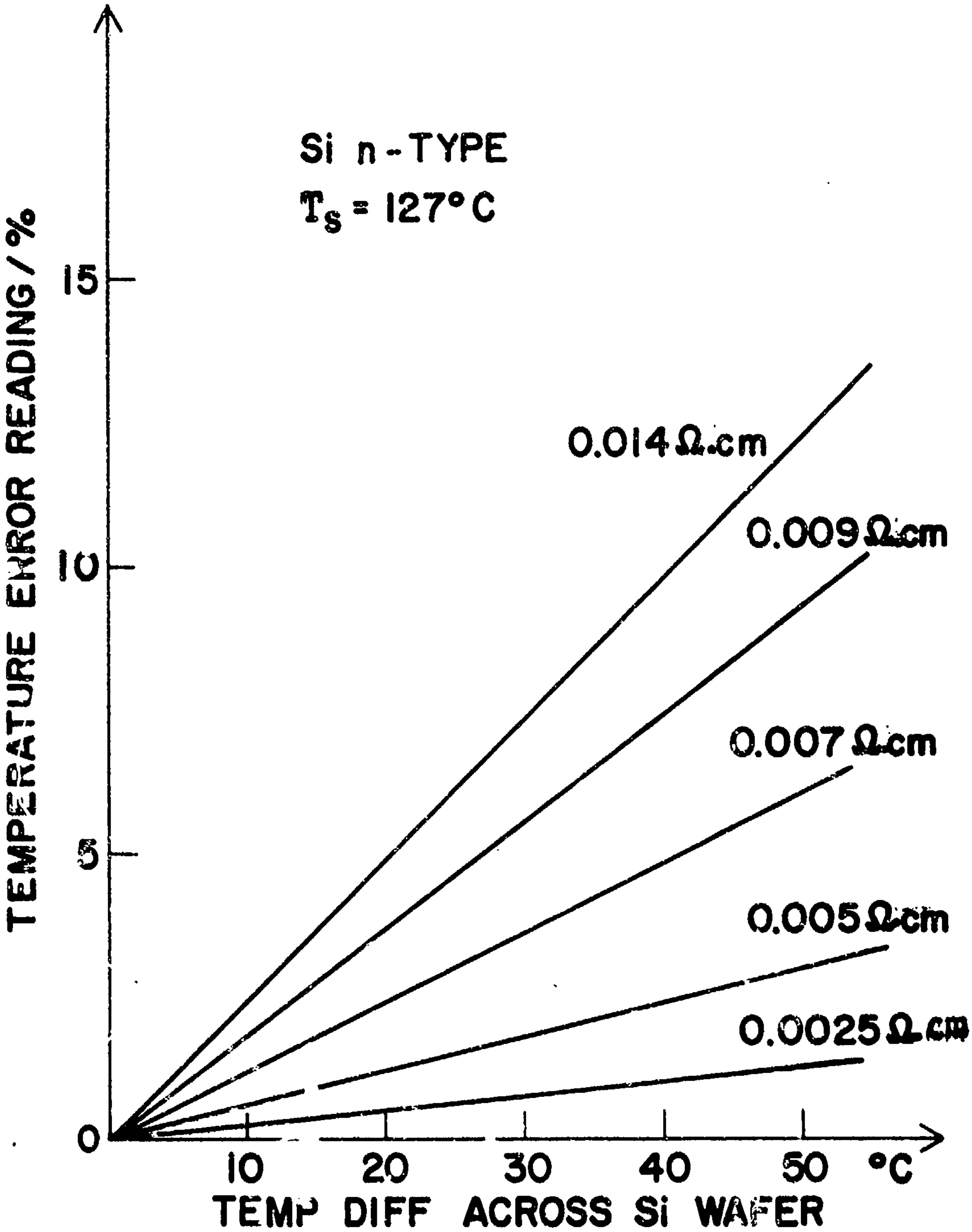

FIG. 3. LOWERING OF TEMPERATURE READING ON n-Si SURFACE AS RESULT OF VERTICAL TEMPERATURE GRADIENT ACROSS THE WAFER FOR VARIOUS RESISTIVITIES