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DIELECTRIC CONSTANT OF GERMANIUM AS A FUNCTION
OF FREQUENCY, TEMPERATURE, AND RESISTIVITY

BY

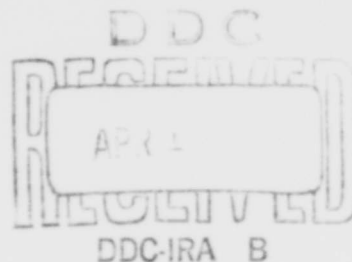
MAURICE A. DRUESNE

JANUARY 1965

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DIELECTRIC CONSTANT OF GERMANIUM AS A FUNCTION
OF FREQUENCY, TEMPERATURE, AND RESISTIVITY

by

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January 1965

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U. S. ARMY ELECTRONICS LABORATORIES
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FORT MONMOUTH, NEW JERSEY

Abstract

The use of semiconductors in electronics has increased tremendously during the last decade and this growth will continue. One of the most important characteristics of semiconductors is the dielectric constant which determines their electrical behavior.

Measurements of the dielectric constant have been made on p- and n-type germanium of various resistivities (20, 10, and $1/2$ ohm-cm). At the same time the dielectric constant has been found to decrease with lower temperatures down to 78°K.

Similarly, the dielectric constant has been measured at various frequencies and was found to decrease with increasing frequency. At very low resistivity ($1/2$ ohm-cm) some anomalous behavior is found which is due to the fact that the material is no longer really a semiconductor, but begins to act as a conductor.

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DIELECTRIC CONSTANT OF GERMANIUM AS A FUNCTION OF FREQUENCY, TEMPERATURE, AND RESISTIVITY

INTRODUCTION

The dielectric constant constitutes an important characteristic of a semiconductor, and affects the static and dynamic properties of devices utilizing it.

The dielectric constant of germanium has been measured by many authors at various frequencies and temperatures, and for a variety of reasons. Benedict and Shockley,¹ for instance, measured it at 1.24 cm for their determination of the effective mass. Goldey and Brown² repeated the measurements at 24 Gc to check the value of the effective mass. D'Altroy et al,^{3,4} have also published results on germanium at 9.2 Gc and low-temperatures in their study of the effect of neutral impurities.

Recently, bulk effects in semiconductors have come to the fore in such applications as maser, laser, hot-carrier thermoelectric effect, phonon parametric amplifier, etc. In these new effects the characteristics of the bulk material become paramount, and some of these effects are utilized at higher frequencies than those for which dielectric measurements have previously been carried out. The present work on dielectric measurement fulfills a current need in measuring the behavior of the bulk dielectric constant more systematically as a function of temperature, frequency, and resistivity at millimeter frequencies. Values are given for arsenic doped n-type and gallium p-type germanium.

MEASUREMENT TECHNIQUE

The measurement of the dielectric constant was carried out at microwave frequency by making use of the standing wave pattern technique. The introduction of the sample into the waveguide produces a change in the standing wave, and this change is the basis for the calculation of the dielectric constant. The theory of this method was established by Roberts and Von Hippel,⁵ and by Westphal.⁶

The reduction of the data leads to a complex transcendental equation:

$$\angle \psi = \frac{\text{Tanh}(T \angle \tilde{\epsilon})}{T \angle \tilde{\epsilon}} \quad (1)$$

that must be solved for T and $\tilde{\epsilon}$. This can be done by programming a computer or by making use of extensive charts published in the literature, and particularly by Westphal.⁶ A much simpler approximate solution to this equation can be readily obtained. The dielectric material in the waveguide can be viewed as a four-terminal structure, and the dielectric constant is then obtained from the determinant of the admittance representation. In this method, however, a great many variations in detail are possible. The particular method adopted consisted of placing the sample right against the moving plunger of the sliding short used to create the standing wave pattern. The sample itself is cut and ground to fit the waveguide exactly. This method provides the advantage of allowing operation of the microwave system in a vertical position which is advantageous for cooling the sample to 78°K by immersion of the sliding short into a dewar containing liquid nitrogen.

Conversely to measure at +60°C, the sliding short is placed over a small electric heater.

The measurements at high microwave frequencies (61.3 and 92 Gc) are difficult to carry out due to the increased instability of the microwave sources. Klystrons, at these frequencies, tend to drift and the power available (of the order of 60 to 70 mw) is barely enough due to the high attenuation in the waveguide system.

At low temperatures, condensation may occur inside the waveguide and thus cause erroneous results. Finally, the length of the sample becomes extremely critical, especially at low resistivities, and a great many readings are required to insure accuracy. A block diagram of the experimental arrangement is shown in Fig. 1.

RESULTS

Dielectric measurements were made on both n- and p-type germanium having the following approximate dc resistivities: 1/2, 10, and 20 ohm-cm. The actual resistivities were as follows:

n-type germanium - 0.563, 11.03, and 17.33 ohm-cm

p-type germanium - 0.315, 12.41, and 18.91 ohm-cm.

All samples were measured at frequencies of 61.3 and 92 Gc, and at four different temperatures ranging from liquid nitrogen to +60°C. The results of all the measurements are plotted in Fig. 2-7 as the dielectric constant as a function of the temperature for the two frequencies 61.2 and 92 Gc.

The following conclusions are noted:

1. For both n- and p-type germanium of 20 and 10 ohm-cm resistivities, the dielectric constant decreases as the temperature decreases, as shown in Fig. 2, 3, 5, and 6.
2. For both n- and p-type germanium of 1/2, 10, and 20 ohm-cm resistivities, the dielectric constant decreases as the frequency increases, as shown in Fig. 2-7.
3. For the p-type germanium of 1/2 ohm-cm resistivity, the dielectric constant decreases as the temperature decreases at 61.3 Gc, but at 92 Gc it remains nearly constant with the temperature, as shown in Fig. 4.
4. For the n-type germanium of 1/2 ohm-cm resistivity, the dielectric constant decreases as the temperature decreases at 61.3 Gc, but at 92 Gc it increases as the temperature decreases, as shown in Fig. 7.

The standard deviation was calculated for groups of readings leading to results shown on the curves, and it varied from a low of $\sigma = 0.15$ to a high of $\sigma = 0.29$. The results are, therefore, in doubt at most by ± 0.30 . The results presented are based upon one sample of each type and resistivity. More reliable data would be obtained if several samples had been put through the two frequencies and the various temperatures. Unfortunately, only one ingot of each type and resistivity was available, thus limiting the data obtained.

Finally, it may seem that the knee in the various curves is arbitrarily located. To a certain extent it may be so, but in three cases a temperature of about -110°C is reached before the dielectric constant begins to decrease. On the strength of this fact the knee of the other curve is placed below that temperature thus assuming that the various samples would behave identically (except the n- and p-type of germanium of $1/2$ ohm-cm at 92 Gc).

CONCLUSIONS

Both n- and p-type germanium of $1/2$ ohm-cm resistivities behave anomalously at 92 Gc as a function of the temperature. The measurements were carefully checked and appear beyond doubt.

In order to explain the behavior of the dielectric constant as a function of temperature and frequency, an attempt was made to calculate the values theoretically. At high frequencies the dielectric constant is given by

$$k(\omega) = k_0 + \frac{4\pi}{\omega} \sigma_1 \quad (2)$$

where:

k_0 = dc values of the dielectric constant

ω = angular frequency

σ_1 = imaginary term of the conductivity as given by:

$$\sigma(\omega) = \sigma_r + i \sigma_1 \quad (3)$$

where:

$\sigma(\omega)$ = conductivity at angular frequency ω

σ_r = real term of conductivity.

At microwave frequencies, therefore, the dielectric constant is a function of the conductivity and this, in turn, is a function of the mobility.

When the frequency reaches a certain value, the carriers can no longer follow the field, the conductivity decreases and so does the dielectric constant. The theoretical study of the dielectric constant as a function of frequency and resistivity is essentially a study of the mobility of the carriers.

The simplest method, and the one tried first, was to assume spherical energy surfaces for a non-degenerate semiconductor. The approach consists of calculating the electrical conductivity on the basis of combining the two scattering mechanisms resulting from the lattice and the impurities.

The neutral impurity scattering was neglected since the temperature was only 78°K.⁷ The two scattering mechanisms can be considered as being independent, and the effective mean free path is given by:

$$\frac{1}{l} = \frac{1}{l_t} + \frac{1}{l_i} \quad (4)$$

where:

l_t = mean free path due to thermal (lattice) scattering

l_i = mean free path due to impurity scattering, some uncertainty attaches to this value of the effective mean free path since it depends upon the value of the effective mass which is itself in doubt.

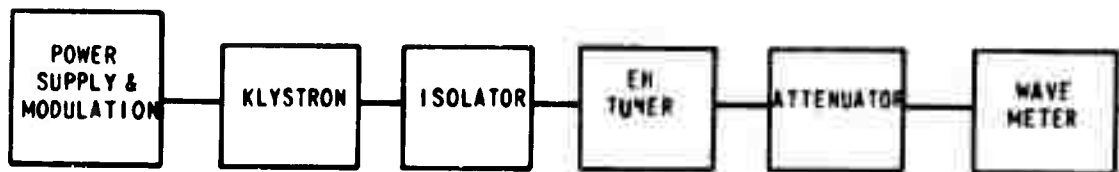
Because of the assumptions made and of the uncertainties involved in the quantities used, this simple theory based on spherical energy surfaces does not yield a satisfactory agreement with the experimental results.

A more sophisticated approach involves the use of the so-called many valley theory⁸ where the energy surfaces are ellipsoids for the non-degenerate semiconductor. But even with the more realistic approach, the results of the experiments and of the calculations still do not agree.

The conclusions to be reached from these attempts is that the present theories of mobilities are inadequate to account for the behavior of the dielectric constant even for high resistivities, let alone the anomalous behavior of the 1/2 ohm-cm resistivity n- and p-type germanium. More experiments and theoretical work are required, especially at low resistivities and millimeter waves.

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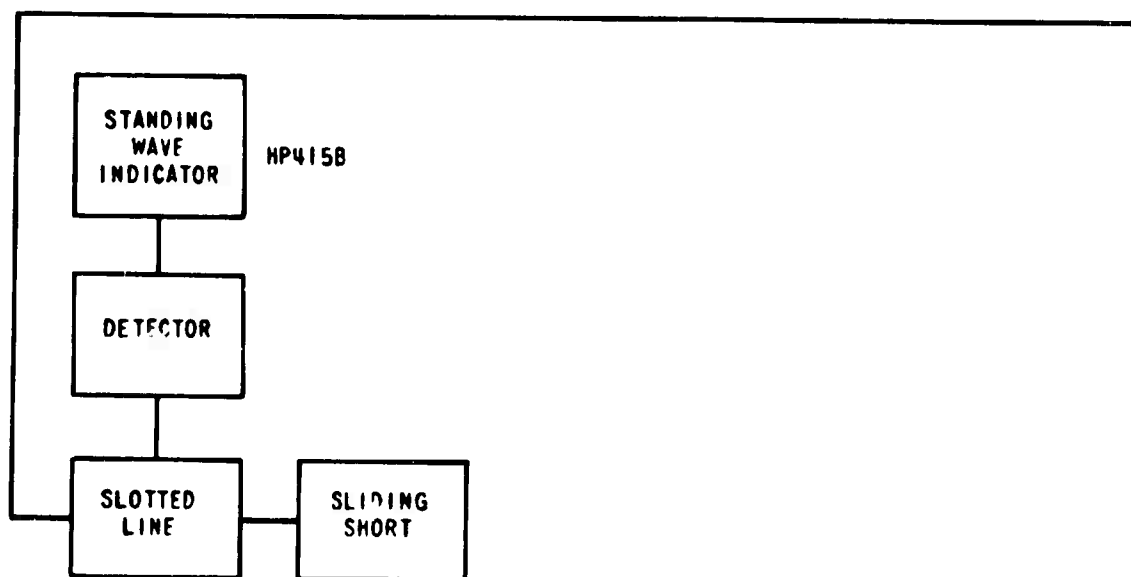


FIGURE 1
MICROWAVE SET-UP FOR DIELECTRIC CONSTANT
MEASUREMENTS

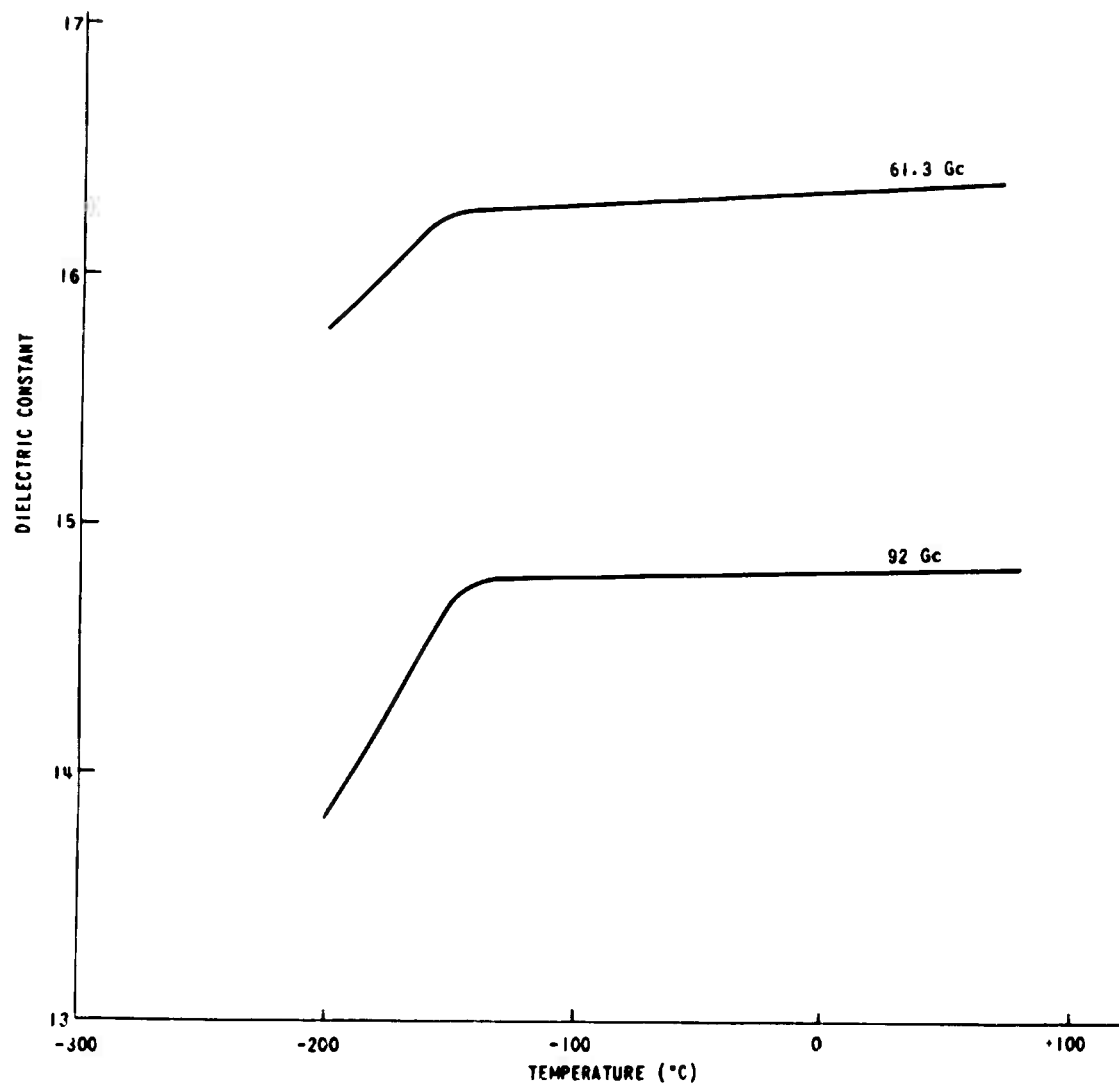


FIGURE 2
DIELECTRIC CONSTANT OF GERMANIUM (P TYPE 20 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

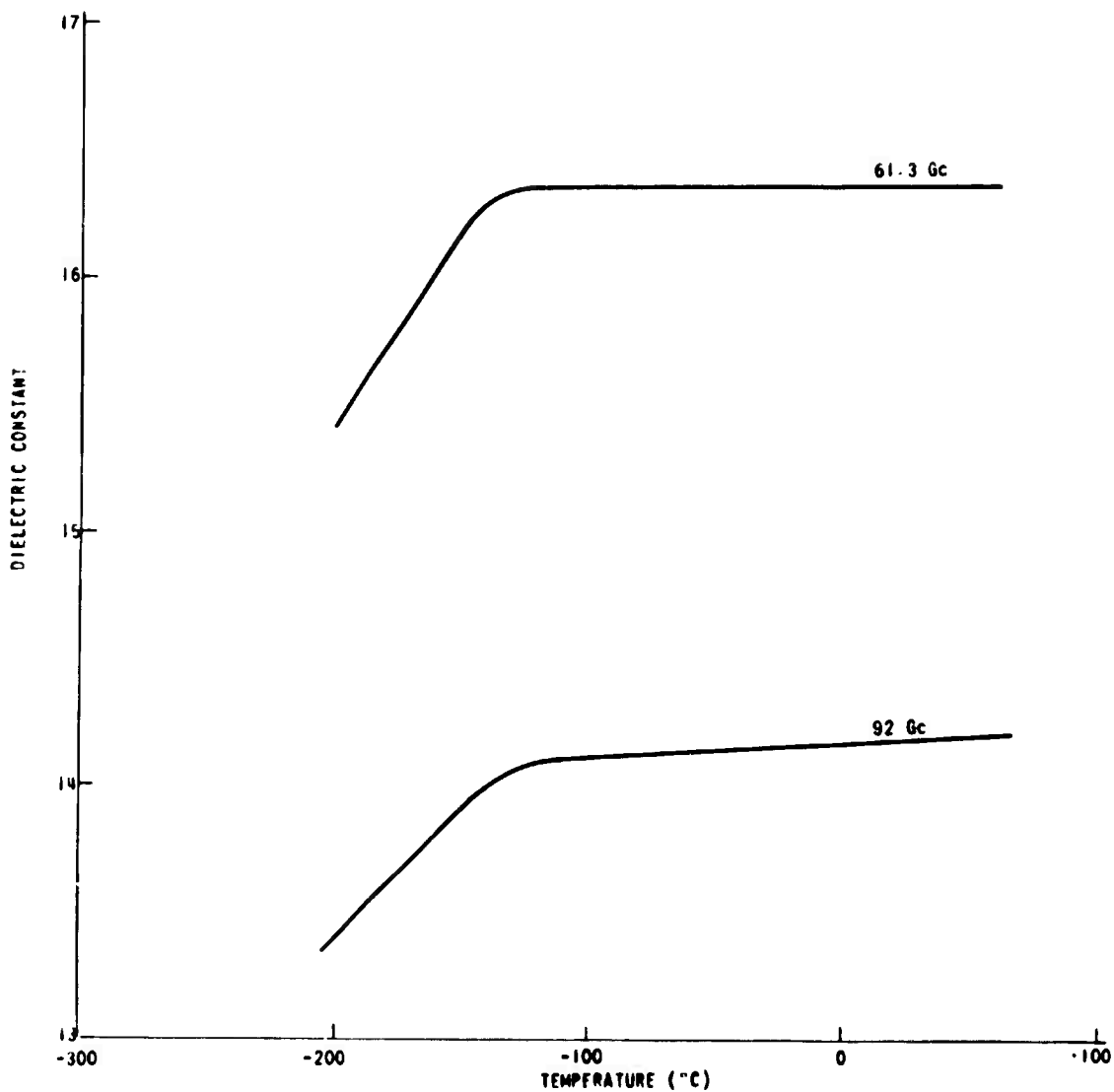


FIGURE 3
DIELECTRIC CONSTANT OF GERMANIUM (P TYPE 10 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

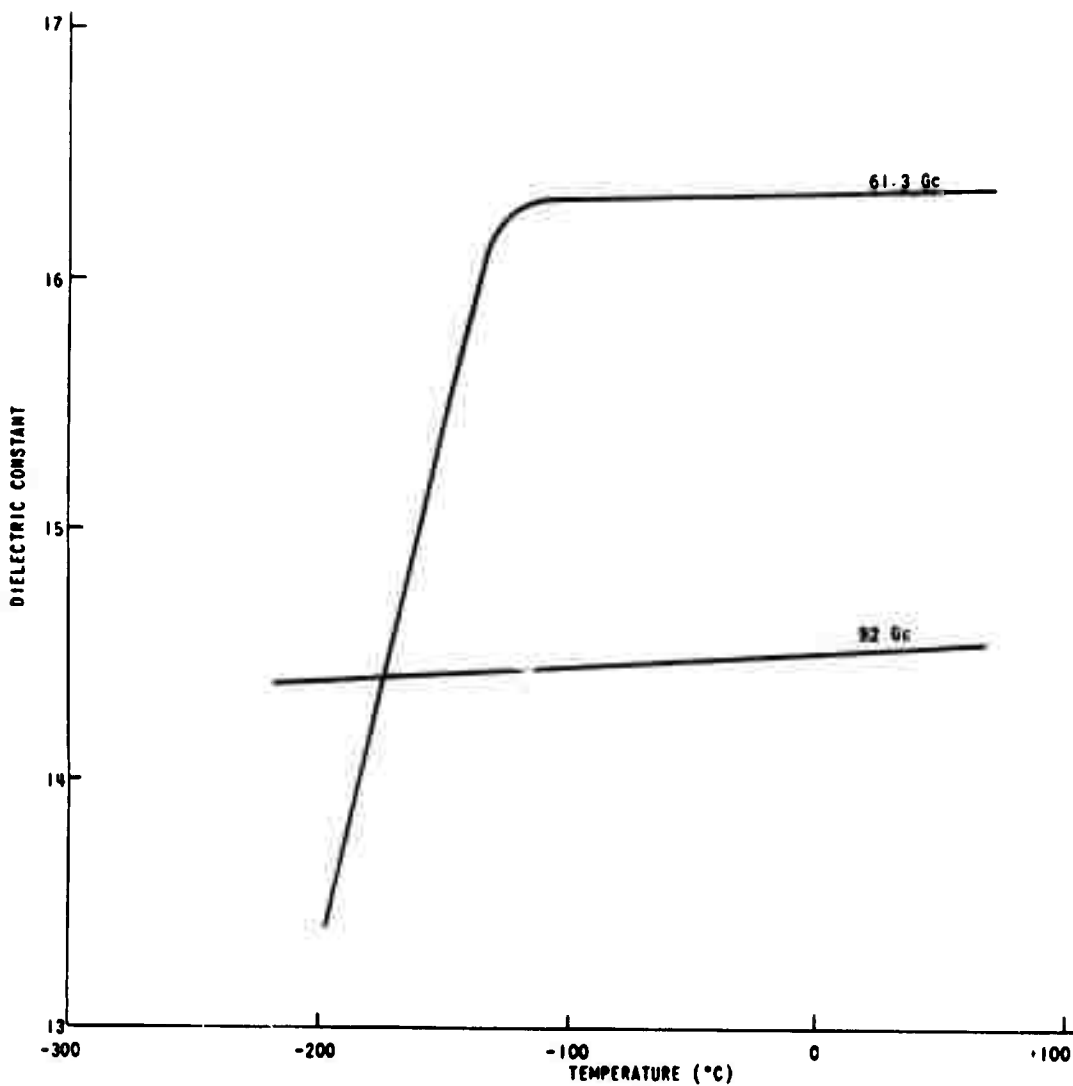


FIGURE 4
DIELECTRIC CONSTANT OF GERMANIUM (P TYPE 1/2 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

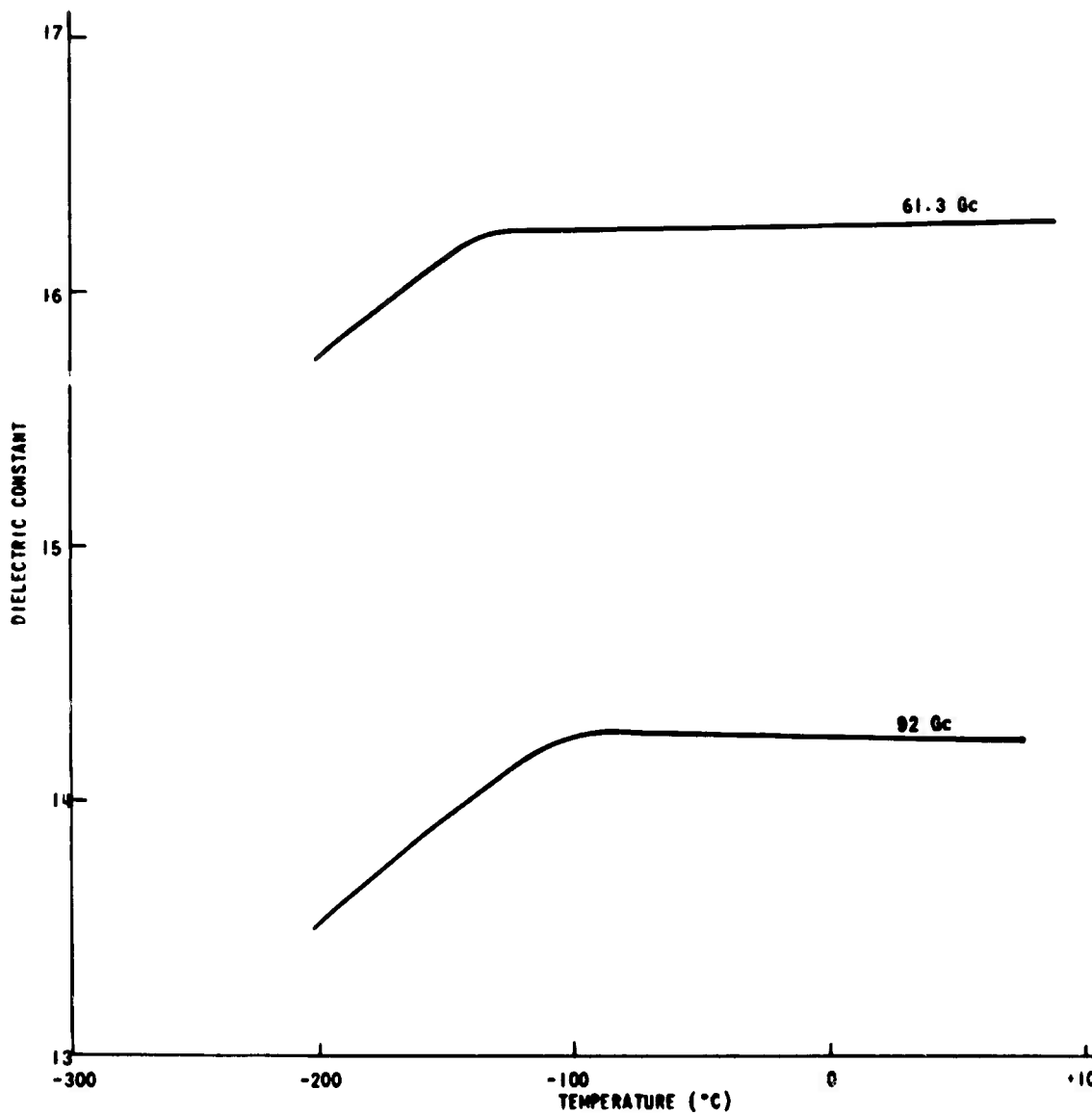


FIGURE 5
DIELECTRIC CONSTANT OF GERMANIUM (N TYPE 20 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

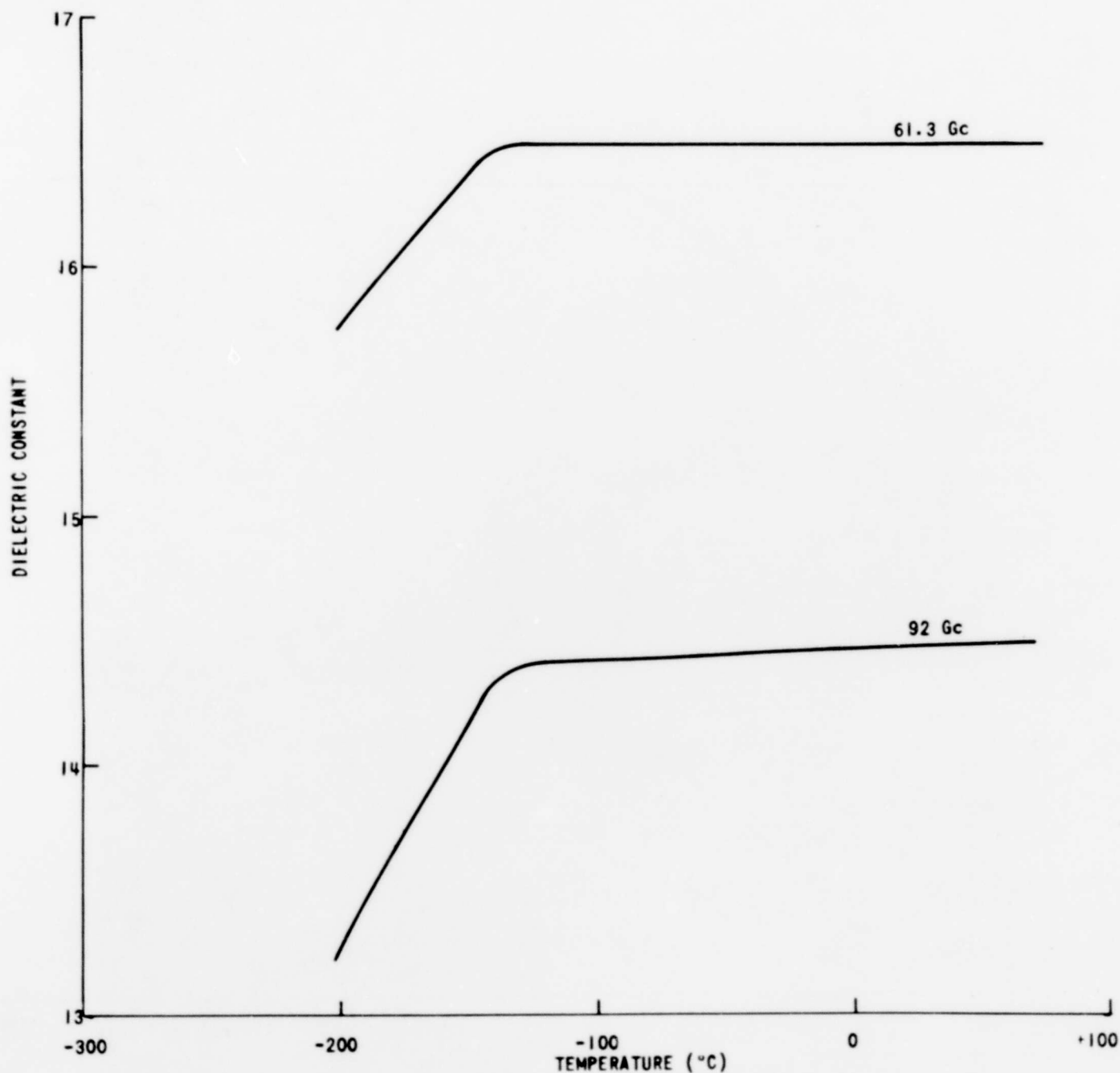


FIGURE 6
DIELECTRIC CONSTANT OF GERMANIUM (N TYPE 10 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

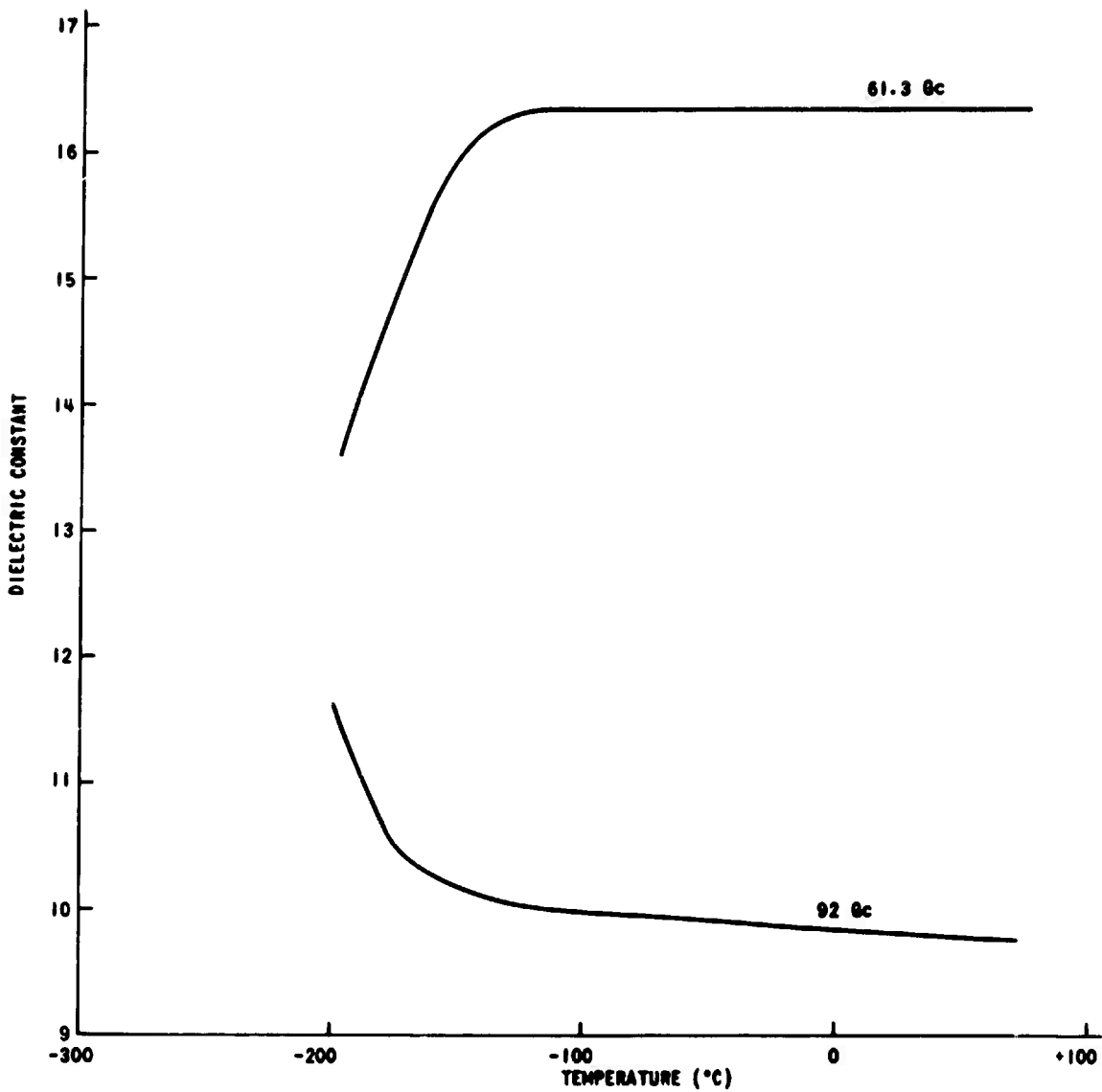


FIGURE 7
DIELECTRIC CONSTANT OF GERMANIUM (N TYPE 1/2 OHM-CM)
AS A FUNCTION OF TEMPERATURE AT 61.3 AND 92 Gc

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