TEMPERATURE CHARACTERISTIC OF AN AC POSISTOR

I. F. Voloshin and S. B. Minkin

Inzhenerno-Fizicheskii Zhurnal, Vol. 13, No. 2, pp. 209–214, 1967

UDC 537.311.33

The temperature characteristic of a new semiconductor thermosensitive element—the ST5-1 ac posistor—is considered. It is shown that the capacitance of an ac posistor depends on the temperature. The general form of a posistor equivalent circuit is considered and its parameters are determined.

In contrast to thermistors, a posistor is a semiconductor temperature-dependent element with a positive temperature coefficient of electrical resistance for a particular range of positive temperatures. The ST5-1 posistors have a positive temperature coefficient of resistance reaching 60%/deg or more.

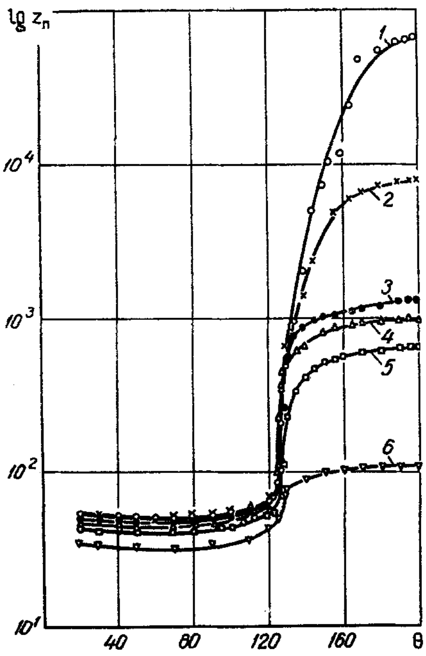

Fig. 1. The modulus of posistor impedance z (in ohms) as a function of the temperature Θ (°C) for different supply-voltage frequencies: 1) $f = 0$; 2) $f = 1000$ Hz; 3) 5000; 4) 10 000; 5) 20 000; 6) 100 000.

This corresponds to at least a three-order change in posistor impedance. In turn, this makes it possible to use posistors as resistance thermometers, temperature regulators, moisture detectors, etc.

At present, we have relatively little data on the characteristics of posistors. Such information is needed to make correct use of these semiconductor elements. In this article the temperature characteristic of the ST5-1 posistor is considered when this device is connected to an ac circuit with various supply-voltage frequencies.

Figure 1 shows experimental curves for the modulus of posistor impedance as a function of temperature for supply-voltage frequencies of 1000 to 100 000 Hz. For comparison, this figure also shows the temperature characteristic of a dc posistor for $f = 0$ (curve 1). It follows from Fig. 1 that the impedance of an ac posistor drops sharply as the supply-current frequency increases. For frequencies down to 20 kHz the manner in which the curves for the posistor temperature characteristics change is almost the same as the manner in which they change for direct current. With further increase in frequency the anomalous rise observed in impedance near the Curie temperature decreases greatly. We have reason to suppose that such a rise can generally cease.

Figure 2 shows the change in the modulus of posistor impedance as a function of frequency when the ambient temperature is taken as the parameter. As is clear from the figure, for temperatures below the Curie point (125–127° C for our posistors), the impedance remains constant down to a frequency $f = 10^4$ Hz and changes very little for frequencies down to $f = 10^5$ Hz. For temperatures above the Curie point (curves 3–5), the modulus of posistor impedance decreases greatly for frequencies as low as 20 kHz; the drop is even greater at higher frequencies. Figure 1 also shows the decrease in posistor impedance as the frequency increases. Thus, posistor impedance at $\Theta = 200°$ C and $f = 100$ kHz is almost a thousand times smaller than for a dc posistor.

An explanation of the manner in which the temperature characteristic of an ac posistor changes (as well as the manner in which $R_p = F(\Theta)$ changes for a dc posistor) must be found by examining the properties of its material. The posistor is made from barium titanate. Such a material possesses ferroelectric properties, and this provides a basis for assuming that these properties are also manifested in a posistor. In fact, in an electric circuit made up of a linear resistance and a posistor, there is a phase shift between the current and voltage. This shows up quite clearly on an oscillograph screen. The magnitude of the phase shift changes as the temperature and supply-voltage frequency change. Figure 3 shows the phase shift between the current and voltage of the posistor as a function of temperature for various supply-voltage frequencies. Comparison of the curves in Fig. 3 shows that the phase angle depends considerably on the supply-voltage frequency. Thus, for frequencies below 20 kHz and temperatures below the Curie point, the phase shift is so small that it is almost unnoticed on the oscillograph screen. This quantity becomes noticeable only for temperatures close to or greater

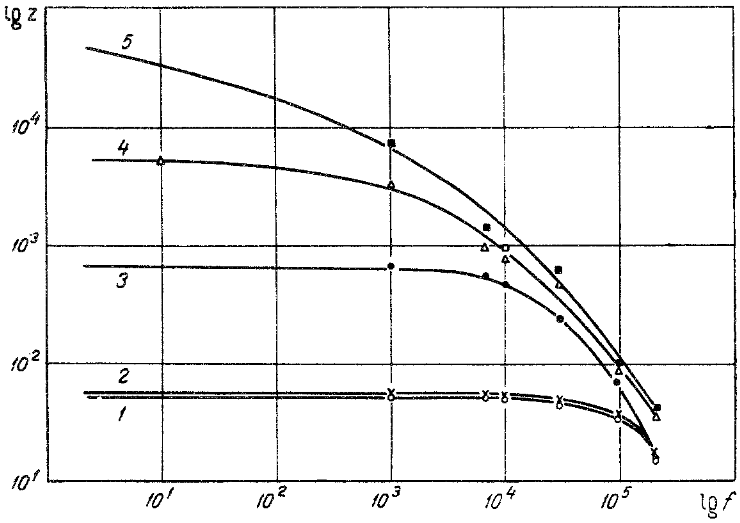

Fig. 2. The modulus of posistor impedance z (in ohms) as a function of supply-voltage frequency f (Hz) for different ambient temperatures: 1) Θ = 20° C; 2) 100; 3) 130; 4) 150; 5) 180.

than the Curie temperature (curve 1 in Fig. 3). At higher frequencies (100 kHz or more), the shift angle is significant even for temperatures below the Curie point. Here, roughly the following relationship between the phase angle and supply-voltage frequency is observed in the initial section of the curve (up to 100° C) for a constant temperature (up to the temperature of line I):

$$\frac{\varphi_1}{\varphi_2} \simeq \frac{f_1}{f_2}. \quad (1)$$

For line II, the curves are more or less equipotential, but the relationship between φ and f no longer agrees with (1).

The presence of a phase shift between the current and voltage indicates that the ac posistor impedance is complex; the fact that the voltage lags behind the current is indicative of the capacitive nature of the reactive component. This makes it possible to represent the ac posistor by the equivalent circuit in Fig. 4a. In the most general case, the posistor can be represented as a nonlinear resistance r_p coupled in parallel to a capacitance C_p whose magnitude depends on temperature. Our representing the posistor by a similar equivalent circuit makes it possible to discover the nature of the processes taking place when a posistor is connected to an ac circuit; this method also makes it possible to determine the dependence of the phase shift and the change in the modulus of posistor impedance on temperature, as well as their changes occurring with supply voltages of varying frequencies.

Moreover, the equivalent circuit makes it possible to determine the active and reactive components of impedance, the values of the equivalent-circuit parameters, and the dependence of these quantities on temperature. Thus, the equivalent circuit of the posistor can serve as a basis for subsequent calculations of electrical circuits employing a posistor as the measuring or control element. We should also note that determination of posistor capacitance by means of an equivalent circuit is the only method possible in some cases, because direct measurement of this

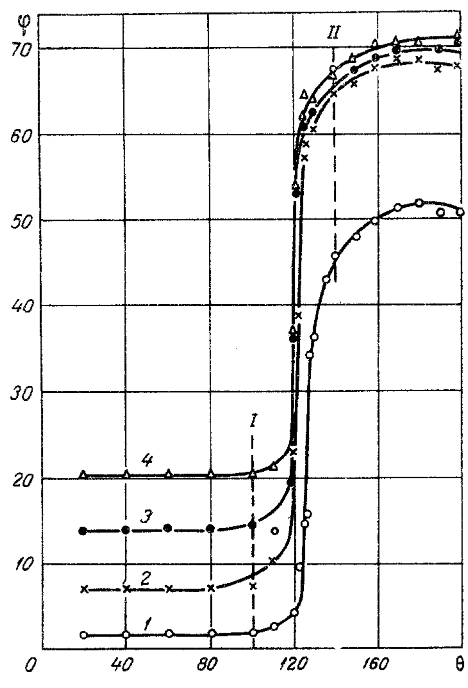

Fig. 3. Phase angle φ (deg) between current and voltage in the circuit consisting of a posistor and linear resistance as a function of the temperature Θ (°C) for different supply-voltage frequencies: 1) f = 20 kHz; 2) 100; 3) 200; 4) 300.

quantity meets with very great technical difficulties owing to high electrical conductivity.

The impedance of the posistor equivalent circuit can be written as

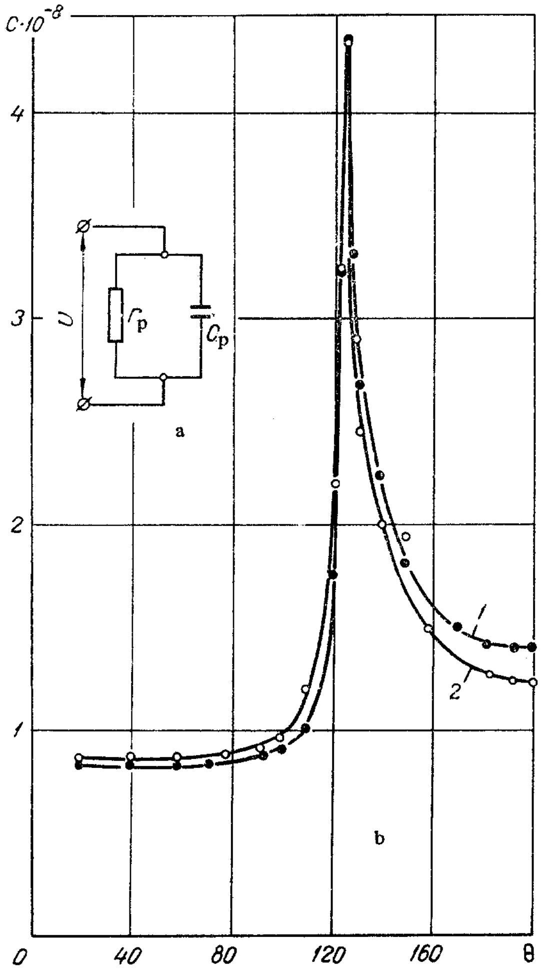

Fig. 4. The equivalent circuit of an ac posistor (a), and posistor capacitance C_p (f) as a function of the temperature Θ (°C) for various supply-voltage frequencies (b): 1) f = 20 kHz; 2) 100.

$$Z = R + jx = \frac{r_p}{1 + \omega^2 C_p^2 r_p^2} - j\frac{\omega C_p r_p^2}{1 + \omega^2 C_p^2 r_p^2}, \quad (2)$$

where the modulus of impedance is

$$z = \frac{r_p}{\sqrt{1 + \omega^2 C_p^2 r_p^2}}. \quad (3)$$

With experimental values for the modulus of impedance and the phase angle φ we can find the active and reactive components of posistor impedance for a given constant temperature Θ, i.e.,

$$R = z \cos \varphi, \quad (4)$$

$$x = z \sin \varphi. \quad (5)$$

On solving the system

$$\left.\begin{aligned} x &= \frac{\omega C_p r_p^2}{1 + \omega^2 C_p^2 r_p^2} \\ z^2 &= \frac{r_p^2}{1 + \omega^2 C_p^2 r_p^2} \end{aligned}\right\}, \quad (6)$$

for C_p and r_p, we obtain

$$C_p = \frac{x}{\omega z^2} = \frac{\sin \varphi}{\omega z}, \quad (7)$$

$$r_p = \frac{z^2}{R}. \quad (8)$$

Thus, expressions (7) and (8) can be used for calculating the capacitance and resistance of a posistor when it is connected to an ac circuit.

Figure 4b shows posistor capacitance as a function of temperature. This graph is plotted with (7). As is clear this figure, the graph of $C_p = F(\Theta)$ is definitely nonlinear with a sharp maximum in the neighborhood of the Curie temperature. It is clear that the curves in Fig. 4b represent on an altered scale the dielectric constant of the posistor as a function of temperature. The curve showing the dielectric constant as a function of temperature for ferroelectric barium titanate has a similar form [2]. This justifies the validity of the equivalent circuit used for the posistor and confirms the presence of properties common to the posistor and ferroelectric $BaTiO_3$.

The fact that the curves $C_p = F(\Theta)$ coincide fairly closely for frequencies of 20 and 100 kHz (Fig. 4b) shows that posistor capacitance in the range indicated does not depend on frequency.

On the basis of our study of the temperature characteristic of an ac posistor we can draw the following conclusions:

1. The ac posistor possesses capacitive properties. The nature of the relation $C_p = F(\Theta)$ is similar to the dependence of the dielectric constant of ferroelectric barium titanate on temperature.
2. The sharp increase in posistor impedance and capacitance in the neighborhood of the Curie temperature is associated with the ferroelectric phase transition of $BaTiO_3$.
3. The characteristic properties discovered for these ac posistors can prove useful when the latter are used as elements in measuring, control, and correction devices.
4. The results obtained, can also serve as a basis for further study of thermal and electrical properties common to posistors and ferroelectrics, and for development of a theory of thermoelectric effects.

NOTATION

Z is the posistor impedance; R and x are the active and reactive components of impedance; z is the modulus of impedance; C_p and r_p are the capacitance and resistance of an ac posistor; f is the supply-voltage frequency; ω is the angular frequency; φ is the phase angle between the current and voltage in the posistor-linear resistance circuit; Θ is the ambient temperature.

REFERENCES

1. A. F. Ioffe, Physics of Semiconductors [in Russian], Izd. AN SSSR, Moscow-Leningrad, 1957.
2. B. M. Vul, Ferroelectricity [in Russian], Izd. AN SSSR, Moscow, 1956.
3. F. Iona and D. Shirane, Ferroelectric Crystals [Russian translation], Izd. Mir, 1965.
4. A. G. Shashkov, Oscillations in Thermistor Circuits [in Russian], Izd. AN BSSR, Minsk, 1963.

24 February 1967

Institute of Heat Transfer and Mass Transfer AS BSSR, Minsk