PHYSICS

Academician of the Academy of Sciences of the Uzbek SSR E. I. ADIROVICH, S. P. LUNEZHEV, Z. P. MIRONENKOVA

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Abstract

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S. P. LUNEZHEV, Z. P. MIRONENKOVA

PHASE-COMPENSATION METHOD FOR MEASURING RELAXATION TIMES OF THE ORDER OF 10^{-10} SEC IN p—n JUNCTIONS *

1. In connection with the development of nanosecond transistor electronics, E. I. Adirovich (1) proposed a phase method for measuring small relaxation times in p—n junctions. He and his coworkers (2,3) also developed the corresponding experimental setup for measuring times $\sim 10^{-8} \div 10^{-9}$ sec. In the work of S. P. Lunezhev (4), the question is discussed of the influence of parasitic capacitances shunting the resistance that sets the ac operating mode of the diode under investigation, and it is shown that this influence is especially significant in the current-generator mode, which in other respects has advantages over the voltage-generator mode. The possibility, shown by E. I. Adirovich, O. E. Kruchenetskii, O. M. Kurbanov, and S. P. Lunezhev (5), of measuring the phase of the diode impedance instead of the phase of the voltage-transfer coefficient or of the total admittance of the circuit makes it possible to eliminate the experimental difficulties associated with the limiting modes of the current generator or the voltage generator.

In solving scientific, as well as production, problems connected with the latest advances in semiconductor electronics, there arises ever more often the necessity of measuring still shorter relaxation times. In the present work a new method is set forth, combining the advantages of phase and compensation measurements and making it possible to move into the region of processes developing in 10^{-10} sec and less. So far as we know, at present there are no methods for studying such rapid electronic processes in semiconductors.

2. It is known that, among all radio-engineering methods of measurement, the greatest sensitivity is possessed by measurements based on determining a phase shift (6). Therefore, with the aid of the phase method it has been possible, by comparatively simple means, to record very short processes occurring in a semiconductor (1–3). However, direct readout entails a number of disadvantages. First of all, it does not make it possible to measure R and C separately. As applied to a diode, this means that, in determining φ, we obtain information about a relaxation process characterized in total by some time τ. What resistance the p—n junction has is

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

> not known, and, if necessary, it must be determined specially on a separate setup. This operation involves unnecessary expenditure of time and additional errors caused by parasitic capacitances; moreover, the smaller τ is, the more difficult these errors are to eliminate. Under the condition of separate determination of the diode' s R and C, the need for a special determination of R disappears, and the correct choice and implementation of the circuit also eliminate the remaining disadvantages listed above. The possibility of measuring both components separately is inherent in the bridge compensation method of measurement ([7–9]). In works ([7,8]), a method was proposed for determining τ based on bridge measurements. However, for reasons discussed below, it is impossible to measure small τ' s by the circuit described in those works.

As is known ([10]), balance in an ac bridge is achieved when two conditions are fulfilled simultaneously: equality of amplitudes and equality of

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the phase of the voltages between the points of the indicator diagonal and the common point of the bridge. For zero indication, an instrument that measures the potential difference is usually used. Balance is achieved in 2–3 steps by alternately adjusting the active and reactive elements of the compensation arm, which may be chosen as any of the arms of the bridge. Other conditions being equal, the sensitivity of the bridge is determined by the sensitivity of the null indicator.

Fig. 1

Fig. 2

Small phase shifts associated with small τ produce only a slight unbalance in the bridge, which even modern balance indicators sensitive to amplitude changes cannot detect. If a phasemeter with a sum-and-difference detector, used in works ([2,3]), is employed as such a balance indicator, it becomes possible to determine the R and C of a diode corresponding to lifetimes $\sim 10^{-10} \div 10^{-11}$ sec, while working at a comparatively low frequency, i.e., preserving the main advantage of the phase method (formula (2.14) from ([3])).

The most suitable bridge circuit for these measurements proved to be a comparison circuit (Fig. 1). In the figure, parasitic capacitances that introduce an error into the measurement of τ are shown by dashed lines.

The argument of the voltage transfer coefficient U_{AD}/U_{CD} is

$$\operatorname{tg}\varphi_{\mathrm{I}} = \frac{\omega\left[R_{1k}(C_{1k}+C_1') - R_{01}C_1'\right]}{1 + R_{01}/R_{1k} + \omega^2 R_{1k}R_{01}(C_1'' + C_{1k})(C_{1k} + C_1' + C_1'')}. \tag{1}$$

The argument of the voltage transfer coefficient U_{BD}/U_{CD} is

$$\operatorname{tg}\varphi_{\mathrm{II}} = \frac{\omega\left[R(C+C'') - R_0C'\right]}{1 + R_0/R + \omega^2 RR_0(C + C'')(C + C' + C'')}. \tag{2}$$

Provided that the second and third terms of the denominators are small in comparison with unity, and also that $R_0C' = R_{01}C_1'$, balance of the bridge is attained if

$$R(C + C'') = R_{1k}(C_{1k} + C_1''). \tag{3}$$

If, in addition, $C'' = C_1'$, which within the experimental error we can quite well ensure, then the balance conditions become extremely simplified:

$$R = R_{1k}, \qquad C = C_{1k}, \tag{4}$$

and, on the basis of (2.23) from work (^{3}),

$$\tau = 2R_{1k}C_{1k}. \tag{5}$$

Let us note two circumstances that follow from the calculation: 1) the condition of smallness of the third terms of the denominators in expressions (1) and (2) is fulfilled the better, the smaller the time constant to be measured; 2) owing to the symmetrical construction of the bridge, an error in the measurement can be caused not by the entire parasitic capacitance C'', but only by $\Delta C_{\mathrm{p}} = C'' - C_1'$.

3. The input device of the phasemeter used in (^{3}) was replaced by the input device shown in Fig. 2. The entire assembly was made symmetrically. The inputs of cathode followers, which make it possible to reduce C' and C_1' to a minimum and thereby reduce the influence of these arms on the balance of the bridge, are connected in parallel with the lower arms of the bridge. Auxiliary arms R_6 and R_{6_1}, serving to obtain the initial balance of the bridge, are mounted in parallel with the upper two arms. Such an input device makes it possible to set up the diode in advance, apply the required bias, and, with the toggle switch in position 1, use the phase rotators to set the balance; then switch the toggle switch to position 2. In this toggle-switch position, balance is obtained roughly in amplitude with the variable R_{1k} and C_{1k} (monitored by voltmeters installed at the input

Fig. 3

Figure 3: Fig. 3

of the sum-difference detector) and accurately in phase (monitored by a microammeter installed at the output of the sum-difference detector). The resistances of the auxiliary and lower arms are selected on a Wheatstone bridge with an accuracy of ±1%. To satisfy the condition $v' \ll kT/q$, the ratio of the resistances of the upper and lower arms must not exceed 10. In that case a high-frequency signal of no more than 2 mV will be applied to the diode. If this ratio is chosen smaller, then the signal on the diode at the same voltage at the phasemeter input will also be smaller. At the same time, however, the possibility of inaccurate measurement increases, since the relative contribution of the lower arms of the bridge to the phase balance grows. The latter circumstance would play no role only in the case of ideal symmetry. In order to increase the sensitivity of the setup, a microammeter 5 times more sensitive than that used in ([2],[3]) was installed at the output of the sum-difference detector. The stability after the replacement remained satisfactory. The introduction of auxiliary balance arms helped to preserve the reproducibility of the results, even at such high sensitivity.

Fig. 3

4. The capabilities of the circuit were checked on the simplest electrical model of a diode, consisting of a parallel connection of a resistor and a capacitor. Standard constant resistors (measured on an MO-47 type bridge) and capacitors (measured on an IIEV-1 type instrument) were installed in place of the diode, and compensation was performed with variable carbon resistors and variable capacitors (air and ceramic), the values of which at each point were measured in the same way as those of the standards. The values of R and C were selected in pairs, on the basis of real conditions encountered in diodes, and with the aim of determining the limiting values of τ that could be measured on the given setup (Table 1). As

Table 1

R_e, ohm	$C_\mathrm{e} \cdot 10^{12}$, F	τ, sec	R_meas, ohm	$C_\mathrm{meas} \cdot 10^{12}$, F	τ_meas, sec
10.0	10.4	$2.1 \cdot 10^{-10}$	9.9	10.3	$2.04 \cdot 10^{-10}$
30.00	2.73	$1.64 \cdot 10^{-10}$	30.07	2.70	$1.62 \cdot 10^{-10}$
30.00	15.3	$0.92 \cdot 10^{-9}$	30.07	15.0	$0.9 \cdot 10^{-9}$
96.6	10.7	$2.07 \cdot 10^{-9}$	97.7	10.4	$2.03 \cdot 10^{-9}$
30.7	140	$0.86 \cdot 10^{-8}$	30.7	142	$0.87 \cdot 10^{-8}$
288.0	28.3	$1.63 \cdot 10^{-8}$	288.7	28.4	$1.64 \cdot 10^{-8}$
5500	2.7	$2.97 \cdot 10^{-8}$	5600	3.21	$3.6 \cdot 10^{-8}$

As is seen from Table 1, in the range $10^{-8} \div 10^{-10}$ sec the agreement is good. By means of nonessential changes in the setup this range can be extended by an order of magnitude both toward still shorter and toward longer relaxation times.

A special check of the reproducibility of the results by repeated measurements of one and the same pair of values showed that the relative error does not exceed 10%. Numerical data for two pairs of values are given in Table 2.

Table 2

τ, sec	Values of the standard resistances and capacitances	R_meas, ohm	$C_\mathrm{meas} \cdot 10^{12}$, F	τ_meas, sec	τ_avg, sec
$4 \cdot 10^{-10}$	$R_\mathrm{e} =$ 30.2 ohm$C_\mathrm{e} =$ 6.63 pF	30.7	6.53	$4 \cdot 10^{-10}$	$4.32 \cdot 10^{-10}$
$4 \cdot 10^{-10}$	$R_\mathrm{e} =$ 30.2 ohm$C_\mathrm{e} =$ 6.63 pF	30.5	7.34	$4.47 \cdot 10^{-10}$	$4.32 \cdot 10^{-10}$
$4 \cdot 10^{-10}$	$R_\mathrm{e} =$ 30.2 ohm$C_\mathrm{e} =$ 6.63 pF	30.0	7.50	$4.5 \cdot 10^{-10}$	$4.32 \cdot 10^{-10}$
$1.94 \cdot 10^{-8}$	$R_\mathrm{e} =$ 69.4 ohm$C_\mathrm{e} =$ 140 pF	69.5	131	$1.82 \cdot 10^{-8}$	$1.86 \cdot 10^{-8}$
$1.94 \cdot 10^{-8}$	$R_\mathrm{e} =$ 69.4 ohm$C_\mathrm{e} =$ 140 pF	69.4	132	$1.83 \cdot 10^{-8}$	$1.86 \cdot 10^{-8}$
$1.94 \cdot 10^{-8}$	$R_\mathrm{e} =$ 69.4 ohm$C_\mathrm{e} =$ 140 pF	68.9	141	$1.94 \cdot 10^{-8}$	$1.86 \cdot 10^{-8}$

In conclusion, we point out the necessity of observing a certain caution when connecting the bias circuit. In order that the capacitance of the batteries, as well as the capacitance and inductance of the measuring instrument, have practically no effect on the bridge balance, they must be connected through resistances sufficiently large compared with the upper arms of the bridge.

Figure 3 gives the results of measurements of relaxation times on planar germanium high-frequency diodes of two types. In all cases a region was observed with a sharp slowing of the rate of decrease of the relaxation time, i.e., the experimental criterion for the dominant role of the lifetime in comparison with other relaxation processes in p—n junctions was fulfilled ([2,3]).

Physico-Technical Institute
Academy of Sciences of the Uzbek SSR

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Note: Figure translations are in progress. See original paper for figures.

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