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IMPROVED Y-BRIDGE FOR REVERSE-BIASED DIODE MEASUREMENTS

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The analysis of an AC bridge is carried out in which a non-linear admittance of a reverse-biased diode is considered. A balance condition and a formula for the correction for non-linearity are derived. An audio frequency Y-bridge is described in which all theoretical conclusions are taken into account. The features of the bridge are demonstrated by an example of measurement.

УЛУЧШЕННЫЙ МОСТ ТИПА Y ДЛЯ ИЗМЕРЕНИЙ ДИОДОВ С ОТРИЦАТЕЛЬНЫМ СМЕЩЕНИЕМ

В работе проводится анализ моста переменного тока, в котором рассматривается полная нелинейная проводимость диода с отрицательным смещением. Получено условие равновесия и формула для корекции нелинейности. Описан мост звуковой частоты типа Y, в котором учтены все теоретические выводы. Характерные свойства моста демонстрируются примером измерения.

I. INTRODUCTION

The region of the space charge (depletion layer) associated with a $P-N$ junction or metal-semiconductor point contact can be regarded as a plate capacitor whose capacitance depends on the magnitude and polarity of an applied voltage. As the effective width of the junction region varies with the applied voltage it is obvious that studying the capacitances of the $P-N$ junction supplies an efficient tool for the impurity distribution analysis.

Calculations of the capacitance of a reverse-biased $P-N$ junction (the barrier capacitance) have been carried out in [1, 2, 3] for the case of the simple gap structure. Generally, the barrier capacitance C may be approximated by the following formula

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$$C^z = AS^z/(U_k - U), \qquad (1)$$

where S is the cross-sectional area of the junction, z is an exponent related to the donor and acceptor distribution in the junction region ($2 \leq z \leq 3$), U_k is the contact or barrier potential, $-U$ is a negative voltage applied to the junction. The parameter A depends on the concentration and distribution of the impurities.

If the junction is abrupt,

$$A = e\varepsilon P_0 N_0 / 2(P_0 + N_0), \qquad z = 2,$$

where e is the elementary charge, ε is the semiconductor permittivity, P_0 and N_0 are the acceptor and donor concentrations in the P and N regions, respectively.

If the junction is linearly graded

$$A = e\varepsilon^2 a/12, \qquad z = 3,$$

where a is the concentration gradient.

The capacitance vs. reverse voltage plot is also influenced by deep levels or bands in the gap. This has recently led to the development of the capacitance spectroscopy, which is nowadays widely used for the study of large gap materials, such as GaAs, GaP, and others, used in light emitting diodes.

Out of the possible methods for the capacitance measurements the most suitable are the AC ones. At a given bias, the admittance Y_3 of the junction can be represented as

$$Y_3 = G_3 + j\omega C_3,$$

where G_3 and C_3 are an equivalent conductance and capacitance of the junction, respectively, and ω is the angular frequency. Unlike the usual network components, G_3 and C_3 depend on the applied voltage. This makes our problem non-linear and imposes some requirements on the measuring method.

The applied AC voltage must be small in comparison to the bias voltage. Furthermore, it is very important that the amplitude of the AC voltage be known and constant during the measuring process. It is the object of the present paper to describe an apparatus that does meet all the mentioned requirements. Its design is based on a thorough analysis of the equivalent circuit.

II. METHOD

The described method is an audio-frequency modification of the method for capacitance measurements quoted in [4]. For the equivalent circuit (Fig. 1) there holds

$$u_0 = \left(\sum_{i=1}^{3} u_i Y_i\right)\left(\sum_{i=0}^{3} Y_i\right)^{-1}, \qquad (2)$$

where Y_1 and Y_2 denote the standard admittances, Y_0 is the input admittance of a balance indicator and Y_3 is the voltage dependent admittance of the junction, $Y_3 = Y_3(U+u_3)$, where U is a DC bias and u_3 is an AC voltage across the junction. The voltages of the equivalent supplies are

$$u_i = U_i \sin(\omega t - \varphi_i),$$

where

$$\varphi_1 = \varphi_2 = 0, \quad \text{and} \quad \varphi_3 = \pi.$$

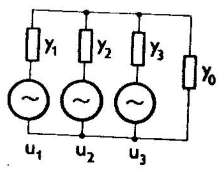


Fig. 1. Equivalent circuit of the bridge.

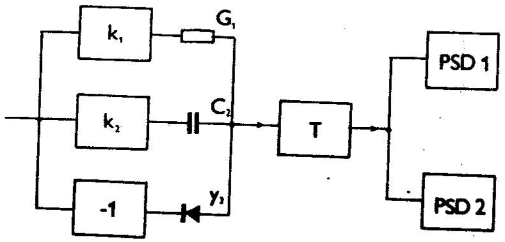


Fig. 2. Block diagram of the bridge

From (2) we get an expression for the voltage u_0 across the balance indicator input admittance:

$$u_0[Y_0 + Y_1 + Y_2 + Y_3(U+u_3)] = u_1 Y_1 + u_2 Y_2 + u_3 Y_3(U+u_3).$$

For simplicity we put

$$Y_1 = G_1, \qquad Y_2 = j\omega C_2$$

and expand Y_3 into a Taylor series:

$$Y_3(U+u_3) = Y_3(U) - \frac{\partial Y_3}{\partial U} u_3 + \frac{1}{2}\frac{\partial^2 Y_3}{\partial U^2} u_3^2 + \ldots,$$

where the symbols $\partial^{(n)} Y_3/\partial U^{(n)}$ mean the partial derivatives of Y_3 with respect to $(U+u_3)$, where it is subsequently put as $u_3 = 0$. The balance condition will be derived, therefore, from the following equation:

$$u_0[Y_0 + Y_1 + Y_2 + Y_3(U) + \mathrm{d}Y_3] =$$
$$= u_1 G_1 + u_2 j\omega C_2 + u_3 G_3 + U_3 j\omega C_3 + u_3 \mathrm{d}G_3 + u_3 j\omega \mathrm{d}C_3.$$

Provided that $|Y_0| \gg |Y_1 + Y_2 + Y_3|$, the harmonic components of the balance indicator current are

$$i_0(\omega) = U_1 G_1 - U_3 G_3 - (3/8) U_3^3 G_3'' + \qquad (3)$$

$$+ j\omega[U_2 C_2 - U_3 C_3 - (3/8) U_3^3 C_3'']$$
$$i_0(2\omega) = -(1/2) U_3^2 G_3' - j\omega(1/2) U_3^2 C_3'$$
$$i_0(3\omega) = (1/8) U_3^3 G_3'' + j\omega(1/8) U_3 C_3'',$$

here G_3', G_3'', C_3', C_3'' denote the partial derivatives in the same sense as above.

The balance condition for the fundamental harmonic frequency is now

$$i_0(\omega) = 0.$$

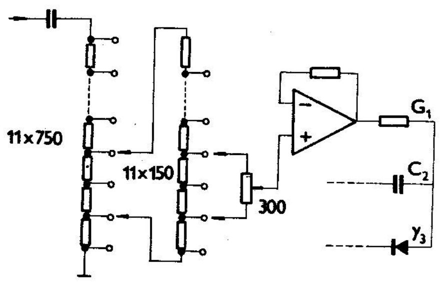


Fig. 3. Simplified circuit diagram of the k_1 potential divider.

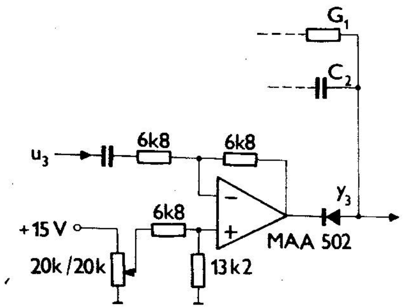


Fig. 4. Simplified circuit diagram of the AC inverter.

If we neglected the terms $(3/8)U_3^3 G_3''$ and $(3/8)U_3^3 C_3''$ we should get the balance conditions

$$G_3(U) = (U_1/U_3) G_1; \qquad C_3(U) = (U_2/U_3) C_2. \qquad (4)$$

As we can see from (1), in general this is hardly the case, particularly for $U \to U_k$, where the partial derivatives C_3'' and G_3'' exhibit rapid variations. For accurate evaluations it is necessary to find the second partial derivatives from the last equation of (3) and subsequently correct the values calculated from (4).

The block diagram of a Y-bridge that was built on the basis of the preceding analysis is in Fig. 2. The voltage from an AF generator is led to a standard conductance G_1 and a standard capacitance C_2 via the calibrated potential dividers k_1 and k_2, respectively. The internal resistance of each of the dividers is at most about $4 \times 10^3\ \Omega$, so that in the audio frequency range the parasitic capacitances and the input capacitance of the following stage play no role. As may be seen from Fig. 3, with respect to the strong negative feedback, the input admittance absolute value is negligibly small in comparison with that of the divider.

The voltage u_0 is fed into the input of a current-voltage converter T. This converter is made up of an operational amplifier with a parallel voltage negative feedback into the inverting input terminal which also serves as the input of the

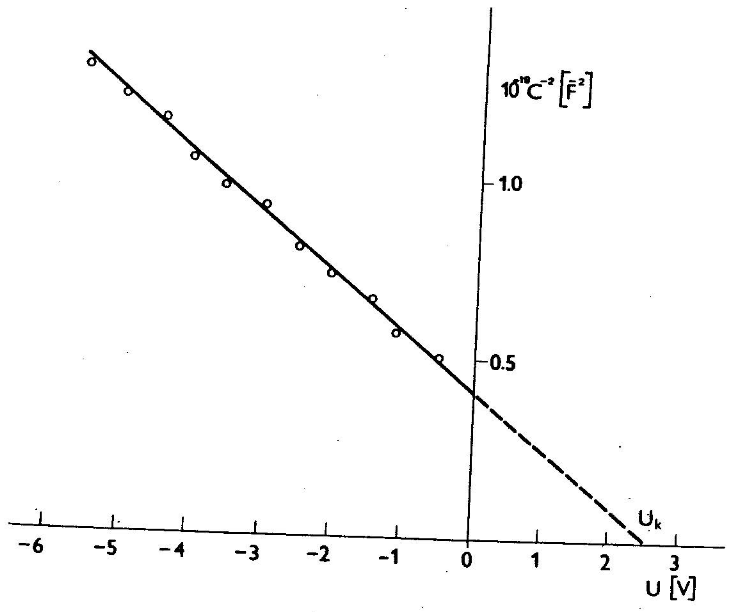


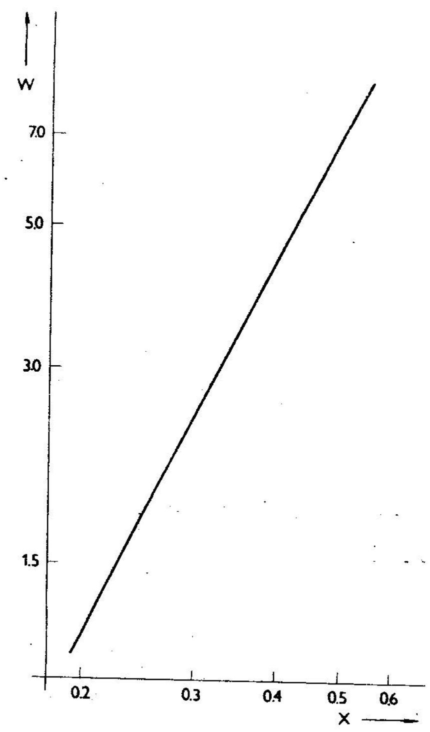
Fig. 5. The C^{-2} vs. U plot for a GaP light emitting diode, sample No V/1.

converter. The input conductance of the converter is very high, so that the input of T makes a virtual ground for the P side of the measured junction and the absolute value of the voltage across the junction equals u_3. The converter output passes to the inputs of two phase sensitive voltmeters PSD_1 and PSD_2. The reference signals of PSD_1 and PSD_2 read G_3 and C_3, respectively, provided the balance is set and the correction for the non-linear terms is made. The standards G_1 and C_2 can be stepwise adjusted within the ranges 100 µS—200 µS and 10 pF—5 nF, respectively.

Fig. 3 shows a simplified circuit diagram of the potential divider k_1 adjusting the ratio U_1/U_3. The divider k_2 setting U_2/U_3 is analogous. With respect to the audio frequency measuring range no frequency compensation of the divider is used.

Fig. 4 shows a simplified circuit diagram of the inverter. While its AC gain is exactly -1, for a DC voltage, tapped from a 20-turn potentiometer, the amplifier has unity gain. The N-side-to-earth capacitance effectively loads the output of the amplifier, the P-side-to-earth introduces a small imaginary component of Y_0. In the simplified circuit diagram of the bridge (Fig. 1.) neither of them, however, influences the balance condition.

Fig. 6. Relative error $w = \delta C_3/C_3$ in percents vs. $x = U_3/(U_k - U)$, for $z = 2$.



III. MEASUREMENT EXAMPLE

As an example of measurement we bring a C^{-2} vs. U plot for a GaP red light emitting diode (Fig. 5). It is seen that $z = 2$, which indicates that the junction is abrupt. The extrapolated value of the contact potential $U_k = 2.5$ V is in good agreement with values reported by other authors.

The calculation of the correction term was carried out numerically. As the measured sample obeys (1), we may write:

$$C_3'' = \frac{1+z}{z}(U_k - U)^{-2}C_3\,,$$

so that

$$\frac{\delta C_3}{C_3} = \frac{3}{8}\,\frac{1+z}{z^2}\,\frac{U_3^2}{(U_k - U)^2}\,.$$

The graphical representation of the last equation for $z=2$ is in Fig. 6. In the region where the readings were taken the correction was less than 0.1 % and, therefore, could be neglected.

IV. CONCLUSION

The Y-bridge described above exhibits many advantages. It can be easily fitted together in a research laboratory. The bias and AC voltages across the sample are adjusted independently and their values are precisely known. The lead-to-earth capacitances of the measured sample do not affect the balance setting. This is of very high importance for temperature dependence measurements, where the sample has to be located in a cryostat and long lead-in wires are inevitable.

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