APPLICABILITY OF THE FLUCTUATION-DISSIPATION THEOREM TO A DESCRIPTION OF NONEQUILIBRIUM NOISE OF SEMICONDUCTOR DIODES

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Grafov and Levich [1] derived recently a fluctuation-dissipation theorem [FDT] that should be applicable to a description of the quasi-equilibrium fluctuations of an arbitrary nonlinear system in a stationary state. For electric noise at high temperature, it is represented in the form of a generalization of the Nyquist theorem

$$\overline{\delta v^2}(\omega) = 4kT\,[R + I\psi], \qquad (1)$$

where δv^2 - spectral density of the noise emf at the frequency ω, k - Boltzmann's constant, T - absolute temperature, R - active component of the impedance at a current I, and ψ - square-law detection defined by the relation $\psi = \Delta V/I_{\sim}^2$, where ΔV - the rectified voltage appearing when a sinusoidal alternating voltage of effective value $I_{\sim}$ passes through the investigated two-pole network. According [1], the fluctuations are assumed to be in quasi-equilibrium if the Gibbs distribution is only weakly violated in the stationary non-equilibrium state.

This paper is devoted to an experimental verification of the generalized FDT, using semiconductor diodes as an example. The choice of diodes as the object of the investigation was dictated by the fact that the requirement that the fluctuations be quasi-equilibrium is apparently well satisfied for carriers in p-n junctions, and it can be assumed with sufficiently good approximation that the carrier temperature differs little from the equilibrium value. This assumption leads to a theoretical expression for the current-voltage characteristic [2]

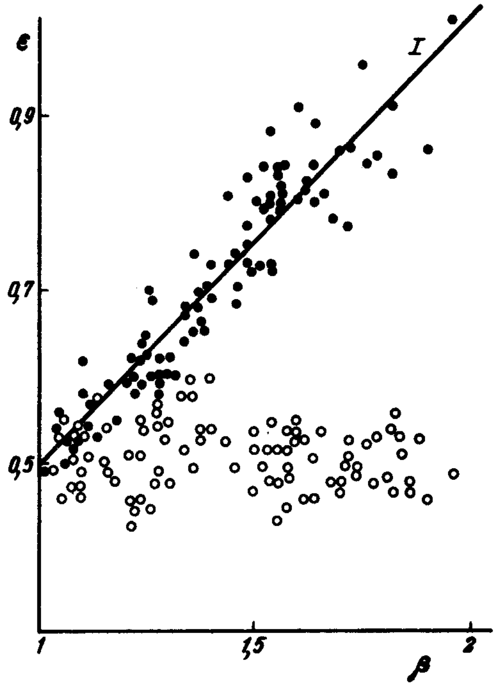
$$I = I_0\left[\exp\left(\frac{eV}{\beta_0 kT}\right) - 1\right], \qquad (2)$$

which is well confirmed experimentally.

The experiments were performed on commercial silicon diodes of the D100 and D242 type, and also on emitter-base and base-collector junctions of the germanium P28 and P39B transistors. The setup for the noise measurement is described in [3], and makes it possible to determine directly the effective noise resistance of the diode $R_n(\omega)$. The impedance was determined with a Tesla-BM401 ac bridge and was represented as a parallel connection of a capacitance C and a conductance G. The square-law detection ψ was determined from the shift of the fixed bias on the diode when a low-amplitude alternating current was applied.

Comparison of the experimental and theoretical values of ε for the base-collector junction of the P39B germanium transistor. Frequency 4 kHz, $\beta_0 = 1.05$.

Current, μA	β^{-1}	δ	$1+\beta\delta$	ϵ_{exp}
−1.0	−1.77	0.435	0.76	0,78
−0.6	−2.30	0.46	0.80	0,83
−0.4	−3,0	0.475	0.84	0.85
−0,25	−4.2	0,48	0,89	0.87
−0,15	−6,3	0,48	0.93	0,92
±0,00	±00	0.48	1,00	1.01
−0,15	5.3	0.47	1,09	1.00
0.25	2.76	0.47	1.17	1.10
0.40	1.41	0.48	1.34	1.30
0,50	0.98	0.48	1.48	1.49
0,60	0.65	0,47	1,72	1,74
0.70	0,42	0,47	2,12	2.18



Comparison of the experimental (o) values of ε and those calculated from (3) (o) for silican diodes. The solid line I corresponds to the Schottky formula for shot noise.

To compare (1) with experiment, it turned out to be expedient to introduce the following dimensionless variables: the noise ratio $\varepsilon = R_n(\omega)/R$ $(R = G/(G^2 + \omega^2C^2)$, the rectification coefficient $\delta = (kT/e)(\Delta V/V_{\sim}^2)$ (e – electron charge, $V_{\sim}$ – effective value of ac voltage on the diode causing the appearance of the rectified dc voltage ΔV), the connection between δ and ψ being given by the formula $\delta = [\psi(kT/e)(G^2 + \omega^2C^2)]$, and the transport coefficient $\beta = eI/kTG$. The quantity β determines in essence the slope of the dynamic current-voltage characteristic measured at the frequency ω. The value of β determined with direct current coincides with the coefficient β_0 of formula (2). Using the indicated variables, we obtain the dimensionless equivalent of formula (1)

$$\varepsilon = 1 + \beta\delta. \tag{3}$$

The results of a verification of formula (3) for a germanium diode ($\beta_0 = 1.05$) are listed in the table. We see that the experimental values of ε and those calculated on the basis of (3) agree within the limits of experimental accuracy (±10%) in the interval $0.7 < \varepsilon < 2$. A similar agreement was obtained for 6 triodes of the P28 and P39B type[1)].

We also investigated a large number of silicon diodes (about 30) with greatly varying value of the coefficient β_0 $(1 \leq \beta_0 < 2)$. In the region of the exponential section of the

1) We do not consider here the low-frequency region, in which the flicker noise is the predominating factor.

current-voltage characteristics it was found that ε, δ, and β depend little on the current or the frequency at sufficiently high frequencies, when the flicker noise is negligibly small. The results of the measurements are systematized in the figure, where the experimental values of ε are plotted. The figure shows also the values of ε calculated on the basis of the generalized FDT (3) using the measured values of δ and β, as functions of the parameter β. We see that the experimental and calculated values of ε coincide near $\beta \approx 1$, but diverge when $\beta > 1$, the discrepancies for diodes with $\beta \approx 2$ greatly exceeding the experimental error. The continuous line I represents the Schottky formula for shot noise, which has in dimensionless variables the simple form $\varepsilon = 0.5\beta$. We see that the Schottky formula is well confirmed for all values of β.

The obtained data show that the generalized FDT agrees with experiment for semiconductor diodes only when $\beta \approx 1$, whereas for real diodes ($\beta > 1$) there is a noticeable discrepancy between the predictions of the FDT and experiment. This discrepancy can be eliminated in principle by formally introducing in (1) and (3) a certain effective temperature $T^* = \beta T$ for the carriers in the diode. This however would contradict the premises of the theory of Sah Noyce, and Shockley [2] ,which describes satisfactorily the current-voltage characteristics of real silicon diodes. According to [2] the values $\beta > 1$ are due to generation and recombination of the carriers in the p-n junction region, whereas their temperature remains close to the lattice temperature regardless of the value of β. It should also be noted in this connection that the generalized FDT is certainly not valid for the description of the generation-recombination noise of linear semiconductor resistors for which $\psi = 0$. The measured noise turns out here to be a quadratic function of the current and can greatly exceed the thermal noise of the active resistance [4]. All the indicated considerations show clearly that the generalized FDT is not a universal theorem applicable to all quasi-equilibrium systems.

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[4] A. Van der Ziel, Fluctuation Phenomena in Semiconductors, Butterworths, 1959.