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RECENT RESULTS OF MODELING OF STATISTIC CHARACTERISTICS OF SEMICONDUCTOR FIELD EMITTERS

R.Z. Bakhtizin, S.S. Ghots and I.M. Chernin-Yakhnuk

Department of Experimental Physics, Bashkir State University, 450074 Ufa, U.S.S.R.

Abstract - The paper considers a model describing experimental results of the study of field emission current low-frequency fluctuations. The model is based upon the assumption of a direct correlation between low-frequency fluctuations with a spectrum $1/f^\gamma$ and electron processes on the emitter surface. We show a one-to-one correlation between the number of emission centres (a feature characteristic for a nonuniform surface) and the low-frequency noise power. The results obtained by means of the model to be presented below have been compared with the Hooge empirical formula. It is shown that the latter provides a satisfactory description of experimental results for frequencies approximating 1 Hz.

I - INTRODUCTION

Taking into account a characteristic size of the active part of semiconductor field emitters, the latter can be classed as a promising type of up-to-date microelectronic devices of the submicron size. The study of noise and statistic characteristics of such objects reveals a number of interesting regularities conditioned by a small amount of conducting particles in the active part of the device. For instance, a marked deviation from the Gauss fluctuation distribution law. It calls for the application of special measures aimed at the elimination of errors in the methods used to measure spectral and moment functions for field emission current fluctuations, with the help of which mathematical model values and experimental data are usually compared. The present paper considers a statistical model of the emitter nonuniform surface, making it possible to clarify certain basic regularities in the appearance of $1/f$ noise in semiconductor field emitters, as well as results of its experimental verification.
II - THE STATISTICAL MODEL OF THE FIELD EMITTER

The given model is based upon the assumption that elementary acts of emission are produced by individual local emission centres (EC) and that each elementary act of emission of a single electron is an elementary current fluctuation. The numerical calculations show that for the dispersion $D(J)$ of flicker fluctuations a simple relation is valid

$$D(J) = J^2/2N$$

where $J$ is the average emission current, $N$ is the number of local ECs.

For the power spectral density of stationary fluctuations the following relations hold true

$$S(f) = \begin{cases} \frac{J^2 f^{-\gamma} \left(1 - \frac{f}{f_U}\right)}{2N f^\delta} & \gamma < 1 \\ \frac{J^2}{2N f \ln \left(f_U/f_L\right)} & \gamma = 1 \\ \frac{J^2 f_{L}^{-\gamma} \left(\frac{f}{f_L}\right)^{-\gamma}}{2N f^\delta} & \gamma > 1 \end{cases}$$

where $f_L$ and $f_U$ denote lower and upper bounds of frequency $1/f^\delta$ noise, respectively.

An attempt to use (2 - 4) for the calculation of $N$ seems tempting but hard to realize for $f_U$ and $f_L$ are unknown values. At the same time, assuming that the nature of EC is this or that, we can find $N$, and thus $f_L$, on the basis of other experiments, the ones that do not depend on the noise measurement.

In the present paper the estimation $f_L = 10^{-8}$ Hz has been obtained proceeding from the fact that total charge density of all the ECs provides a complete screening of the field with a strength of $E = 10^7$ V/cm.

The possibility of parallel spectral analysis with great amounts of information processed by means of up-to-date microcomputers has permitted us to perform a correct spectral analysis of essentially quasistationary fluctuations of the field emission current.

III - EXPERIMENTAL

The spectral analysis of the fluctuations has been carried out by means of the equipment based upon the microcomputer with operational
Fig. 1 - Oscillogram of the low-frequency fluctuations realization. One can see the splashes, resembling the burst noise. The parallel spectral analyzer is necessary for the spectral analysis of such fluctuations.

Table I

Coefficients of approximation of flicker fluctuation realizations

<table>
<thead>
<tr>
<th>Realization N</th>
<th>S [A²·s]</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.38 × 10^{-24}</td>
<td>1.085</td>
</tr>
<tr>
<td>2</td>
<td>8.13 × 10^{-24}</td>
<td>1.081</td>
</tr>
<tr>
<td>3</td>
<td>3.39 × 10^{-25}</td>
<td>1.086</td>
</tr>
<tr>
<td>4</td>
<td>7.94 × 10^{-25}</td>
<td>1.14</td>
</tr>
<tr>
<td>5</td>
<td>1.44 × 10^{-24}</td>
<td>1.278</td>
</tr>
<tr>
<td>6</td>
<td>2.51 × 10^{-24}</td>
<td>1.317</td>
</tr>
<tr>
<td>7</td>
<td>1.07 × 10^{-24}</td>
<td>1.218</td>
</tr>
<tr>
<td>8</td>
<td>2.57 × 10^{-24}</td>
<td>1.231</td>
</tr>
<tr>
<td>9</td>
<td>1.15 × 10^{-24}</td>
<td>1.325</td>
</tr>
<tr>
<td>10</td>
<td>1.99 × 10^{-24}</td>
<td>1.375</td>
</tr>
<tr>
<td>Average</td>
<td>(1.4 ± 0.5) × 10^{-24}</td>
<td>1.21 ± 0.06</td>
</tr>
</tbody>
</table>
The emitters have been prepared from p-type Si single crystals with resistivity 2000Ω·cm. The measurements have been carried out in the vacuum 10⁻⁸ Pa in the frequency range 0.02 - 10 Hz. High frequency filter has been connected to preamplifier input to eliminate direct influence of flicker noise low-frequency components. Fast Fourier transform programme permits spectral analysis of 1024 points in each collection with the subsequent averaging of equal-frequency spectral components obtained by the treatment of 104 collections. The parameter has been determined by the method of least squares, based upon the treatment of 512 unequal-frequency values Š(f). Fig. 1 presents the oscillogram of field emission current fluctuations, while Fig. 2 depicts the dependence Š(f) at a log-log scale.

Fig. 2 - Dependence of the power spectral density of the field emission current noise on the frequency for two different realizations with various coefficients K of approximation: 1 - K=1.08; 2 - K=1.3
Repeated measurements of fluctuation spectra have shown that, experimental conditions (emission current, temperature, anode voltage, light illumination) being fixed, the magnitude $\gamma$ varies. Table I presents values $S(f)$ measured for 10 realizations, which show that the mean value of $\gamma$ constitutes $1.21 \pm 0.06$ at a reliable probability $0.95$, and the mean value of power spectral density of fluctuations $S = (1.41 \pm 0.05) \times 10^{-24} \text{ A}^2 \text{ Hz}^{-1}$ at the same reliable probability. It is interesting to note that statistical accuracy of $\gamma$ within one noise process realization is not worse than $1 \cdot 10^{-3}$ which is at least 10 times less than the spread in the values of $\gamma$ within different noise realizations. Parameter $\gamma$ remains above 1 in all the realizations. This fact has permitted to choose for fluctuation spectra modeling the relationship (4).

IV - Discussion

The results of the modeling, suggested in this paper, make it possible to single out the following reasons of disagreement between the empirical Hooge formula /4/ and experimental results.

1. Parameter $\gamma$ differs from 1 and instead of (3) it is necessary to use (4) or (2).

2. At $\gamma = 1$, according to (3), we get Hooge coefficient $\alpha = 1/2 \cdot \ln(f_U/f_L)$, i.e. it depends on $f_L$ and $f_U$ which are different for different samples.

3. Fluctuations under consideration represent a quasistationary process.

A marked disagreement of (2-4) with the Hooge empirical formula /4/ may be avoided if in the Hooge formula:

$$ S(f) = \frac{\gamma^2 \alpha}{\pi f} \quad (5) $$

there will be used frequencies approaching by an order of magnitude 1 Hz. It is at these frequencies that the study has been undertaken. Assuming $\alpha = 2 \cdot 10^{-3}/4$ /4/ and proceeding from (4) and (5), we get for $f_L$:

$$ f_L = \left[ \frac{2\alpha}{\gamma - 1} \right]^{1/\gamma - 1} \quad (6) $$

Substituting into (6) concrete values for $\gamma$ we get

$$ f_L \approx 10^{-8} \cdot 2 \text{ Hz} \approx 6.4 \cdot 10^{-9} \text{ Hz} \approx 10^{-8} \text{ Hz}. $$

The obtained estimation shows a good agreement with the above-given
estimation made proceeding from the electrostatic laws of external field screening. Besides, the obtained data testify to the validity of the Hooge formula for the estimation of the power spectral density of the semiconductor field emission current fluctuations at frequencies approximating 1 Hz. The Hooge formula for the description of $1/f$ fluctuations, modified, allowing for (4-6) will then acquire the form

$$S(f) = \frac{j^2 \alpha}{N \cdot f} \quad , \quad (7)$$

where $\alpha = 2 \cdot 10^3$, as it is in (5).

REFERENCES