Low noise characteristics of Schottky diode with deep energy level

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Abstract—Results of temperature and electric field dependencies of low-frequency noise power spectral density are presented.

Keywords—low-frequency noise, semiconductor structure, Schottky contact, deep level

I. INTRODUCTION

Investigation of deep levels (DLs) influence on the properties of semiconductor structures is still of interest. Low frequency noise (LFN) spectroscopy is a method that allows investigating semiconductor barrier structures and defining DL parameters.

II. SAMPLES AND INVESTIGATION METHODS

N-type silicon-based test structures in the form of Schottky diodes were manufactured according to the standard industrial technology. In the course of the study, a set of five samples was considered. All samples were performed as a single chip. Al Schottky contacts were created in the form of a square with the side of 2 mm.

At the present work an automated measurement complex was used to study the electrophysical parameters of materials and barrier structures including the Agilent E4980A RLC meter, low-noise preamplifier and voltage offset circuit with galvanic batteries (Fig. 1). As a measuring cell the Janis CCS-400/204N helium closed type cryostat working in the vacuum in the temperature range of 7-500 K was used [1, 2].

Fig. 1. The block diagram of the measuring complex to investigate electrophysical and noise characteristics of semiconductor structures

The experimental values of the parameters were recorded using the data acquisition board NI PCIe-6361 and processed by a special program executed in the LabVIEW environment.

In order to investigate the parameters of deep levels in semiconductor barrier structures current-voltage (I-V) and capacitance-voltage (C-V) characteristics, power spectral density (PSD) of LFN including at different temperatures, noise-voltage characteristics (N-V) were obtained.

The ionization energy of deep energy levels was determined by two independent methods, by plotting Arrhenius plots and by the temperature and electric field dependence of the noise PSD according to the activation-drift model (ADM) and the Pool-Frenkel effect.

EXPERIMENTAL RESULTS

I-V and C-V dependencies of the samples had the form typical for the metal – semiconductor type Schottky barrier structures (Fig. 2-3).

Fig. 2. I-V characteristics of the samples at reverse bias

Presentation of C-V characteristics presented in the Mott-Schottky coordinates allowed calculating the shallow donor concentration in the semiconductor according to the expression [3]:

\[ N = \frac{2}{q \varepsilon \varepsilon_0 S^2} \frac{1}{d(V/C^2)/dU}, \]

where \( q \) is the elementary charge, \( \varepsilon_0 \) is the electrical constant, \( \varepsilon \) is the dielectric permittivity of semiconductor, \( S \) is the area of the Schottky contact, \( C \) is the capacitance of the depleted layer, \( U \) is the reverse bias voltage.
Therefore the potential barrier height at the metal-semiconductor interface was 0.63 eV. The concentration of free electrons in silicon was $6 \times 10^{15} \text{ cm}^{-3}$.

Each type of DL has its relaxation time that depends on the temperature. In the theory of LFN spectroscopy the correspondence of frequency $\omega$ to relaxation time $\tau$ of a particular process is expressed by changing the slope of the spectrum curve and is manifested in the form of its "bend" which is expressed by the equality $\omega \tau = 1$.

According to Boltzmann law the relaxation time is

$$\tau = \tau_0 \cdot \exp \left( \frac{\Delta W_i}{k_B T} \right),$$

(2)

where $\Delta W_i$ is DL ionization energy, $T$ is the temperature, $k_B$ is the Boltzmann constant. Physical meaning of $\tau_0$ differs depending of applying model [4]. In works [5, 6] parameter $\tau_0$ is the characteristic time that is determined by the period of the natural oscillations of atoms in the crystal lattice of semiconductor and $\tau_0$ has the order $10^{-12}$ s.

In practice the ionization energy of deep trapping levels $\Delta W_i$ is determined using Arrhenius plots of experimental dependencies. DL ionization energy $\Delta W_i$ is found from the slope of the Arrhenius line which is represented as

$$\ln \tau = \ln \tau_0 + \frac{\Delta W_i}{k_B T}.$$  

(3)

The values of the DL ionization energy in the studied barrier structures are determined from the experimental low-frequency noise spectra obtained at a bias voltage of -7.9 V and temperature values from 90 to 290 K (Fig. 4). Based on experimental dependencies Arrhenius plots were drawn in semi-logarithmic coordinates and the slope angle proportional to $\Delta W_i$ was found.

Spectrum analysis showed the presence of inflection points at a number of frequencies in the range of Hz units at three temperature regions 100-140 K, 160-190 K and 270-290 K. This indicates the presence of three DLs. By splitting the noise spectra into two sections and approximating those with straight lines the values of the bend frequency were calculated and the Arrhenius plots for the low frequency region were drawn (Fig. 5). The values of the DL ionization energy for the sample obtained in this way are presented in the Table 1.

**Table 1. Parameters of DLs obtained from the PSD temperature dependence**

<table>
<thead>
<tr>
<th>Deep level</th>
<th>DL1 (meV)</th>
<th>DL2 (meV)</th>
<th>DL3 (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta W$</td>
<td>101</td>
<td>107</td>
<td>279</td>
</tr>
<tr>
<td>$\tau_0$ (s)</td>
<td>$1.86 \times 10^{-6}$</td>
<td>$2.63 \times 10^{-5}$</td>
<td>$1.76 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

The method of determining of the ionization energy of DLs developed in this work is based on the measuring of the experimental PSD noise spectrum at the constant temperature and determining the bend frequency of the LFN PSD curve.

According to ADM theory at a sufficiently high reverse bias all activated from DL charge carriers are transferred through the space charge region (SCR) of the barrier structure during the Maxwell relaxation time $\tau_M$ determined by the resistivity of the base [7].

According to the Poole-Frenkel model developed by the authors of this work the ionization energy of deep levels can be calculated according to the expression

$$\Delta W_i = k_B T \ln \left( \frac{1}{4\pi\hbar \cdot \tau_m} \right) + q \sqrt{\frac{qN(\Delta U_k - U)}{2e\varepsilon_0}},$$

(4)

where $\tau_m$ is the mean relaxation time, $q$ is the magnitude of the electronic charge, $\varepsilon_0$ is the vacuum permittivity, and $\Delta U_k$ is the barrier height at the metal-semiconductor interface.
where $f_b$ is the frequency of the PSD curve bend, $U_k$ is the contact potential difference.

The bend frequency of the PSD curve at room temperature was about 350 Hz (Fig. 6) for five samples. The $U_k = 0.4$ V estimated from the C-V measurements was used to find $\Delta W_t = 0.54$ eV.

Investigation of LF noise PSD showed the presence of an additional inflection point in the frequency range from tenths to units Hz. It was found that the samples #2 and #3 had no bend in the low-frequency region, so that the values of LF noise PSD are almost the same. At the same time their I-V and C-V characteristics coincide.

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Fig. 7. LF noise PSD of the sample #1 under the different reverse bias values

One of the advantages of the functional dependence is that it satisfactorily describes the N-V characteristics when considered both on a linear and logarithmic scale.

For the sample #1 measurements of LF-noise PSD were carried out at different reverse bias voltages in the range of 1.4-20.2 V (Fig. 7). Several frequency values were selected from the obtained data array and N-V characteristics were measured (Fig. 8).

All characteristics had the region of initial increase which passed into a site of saturation after some value of tension. The functional dependence that best describes the N-V characteristics had the form

$$PSD = B \exp(U'),$$

where $B$ and $\gamma$ are characteristic coefficients.

It was found that the coefficient $\gamma$ was about 0.5 at all frequencies which corresponds to the Pool-Frenkel model [3].

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The dependence shown in Fig. 9 indicates a proportional increase in the value of the decrease in the DL's ionization energy with an increase in the applied electric field.

The correlation between the value of the bend frequency and the applied voltage at the high-frequency section of the low-frequency noise spectrum was established while no such correlation was observed in the low-frequency region (Fig.10).
The results shown in Fig. 9 and 10 confirm the model developed by the authors according to which the Pool-Frenkel effect proposed to describe the phenomenon of decrease in the activation energy of shallow energy levels at low temperatures. It can be applied to the description of relaxation processes involving DLs in the semiconductor barrier structures at elevated temperatures.

In accordance with the experimental results LFN magnitude may differ by 2-3 orders for semiconductor structures manufactured in a single technological cycle and located in close proximity to each other. Still I-V and C-V characteristics of such structures may be compatible. The experiments proves a higher sensitivity, information content and prospects of LFN-analysis method application to predict potentially unreliable structures and threshold parameters of semiconductor devices in comparison with I-V and C-V methods.

CONCLUSION

The developed physical model of low-frequency noise generation taking into account the influence of DLs is confirmed by experimental results. The Pool-Frenkel model that states potential barrier lowering in the vicinity of a defect that forms a deep energy level in the band gap of a semiconductor under the influence of a strong electric field was proved by experimental data. This model developed for the case of small energy levels at low temperatures can be applied to the case of deep energy levels at relatively high temperatures.

Investigation and modeling of low-frequency noise PSD on voltage dependence is important in both theoretical and practical way. Firstly, this dependence reveals the electric field strength role in the formation of barrier structures current noise component.

Value of the electric field lead to span saturation of charge carriers activated from DLs in a specific structure is still unknown. According to [8] the average electric field strength in the barrier structures SCR must be at least $10^4 \text{ V/cm}$ to obtain reliable data on DL characteristics. At the same time average field strength should not exceed the value of $10^5 \text{ V/cm}$ when breakdown may occur. $\tau_e$ on SCR electric field strength dependence is still not clear. The solution of this issue is the goal for further research.

ACKNOWLEDGMENT

This work is done by support of the Ministry of Science and Higher Education of the Russian Federation (8.8760.2017/B4) using equipment of Regional Center of Probe Microscopy for collective of Ryazan state Radio Engineering University.

REFERENCES


