# Stochastic Resonance in $VO_2$ Thin Films

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*Abstract* – **The phenomenon of stochastic resonance was found in vanadium dioxide films with conducting channel. Experimentally observed transfer coefficient of signal-to-noise ratio amounted of 250 in scheme. By adjusting input noise power it became possible to amplify amplitude of input signal in ratio of 1.6. The computer model was suggested to explain experimental dependencies of signal-to-noise ratio via input noise power.**

***Index Terms*** **– Stochastic resonance, vanadium dioxide, signal-to-noise ratio.**

## I. INTRODUCTION

THE EFFECT OF STOCHASTIC resonance was discovered about 20 years ago. It is one of the examples of noise-induced transitions in a nonlinear system driven by both data signal and noise. The essence of the phenomenon lies in the fact that addition of certain noise intensity can lead to increasing of signal-to-noise ratio [1]. If we take a linear electrical system, the harmonic components of the signal and noise pass through it independently without interfering. In nonlinear systems a correlation exists between noise and signal, and in such cases may arise favorable conditions for weak signals separation from noise.

Vanadium dioxide ($VO_2$) undergoes semiconductor-to-metal phase transition at $T_c = 67^\circ C$ [2]. Above $T_c$ $VO_2$ is metal with a tetragonal lattice, and below $T_c$ it is a semiconductor with a monoclinic lattice symmetry and a band gap of about 0.57eV accordingly [3]. Electrical resistance of the film in a narrow temperature range (about 10°C) changes by more than 3 orders of magnitude. Thus, even slight Joule heating by current leads to a significant change in the resistance and $VO_2$ film can be used as a nonlinear element of the electrical system.

## II. PROBLEM DEFINITION

There are missing data on stochastic resonance in vanadium dioxide films in literature except for [4], with no current-voltage characteristics of $VO_2$ structure presented, that complicates interpretation of results. Vanadium dioxide has found wide application in the creation of various kinds of sensors [5]; therefore, it is of practical interest to study stochastic resonance in circuits with $VO_2$-based structures. In the present work film of vanadium oxides was fabricated in which narrow conductive channel of vanadium dioxide was formed. The phenomenon of stochastic resonance was first investigated experimentally, and then modeled by computer.

## III. EXPERIMENTAL RESULTS

In the experiment, we used structures of $VO_2$ with conductive channel. For vanadium oxides films growth was used method of ion-beam sputtering deposition [6]. Metal vanadium was used as a target for sputtering. Sputtering was carried out in the presence of oxygen, which was fed into a vacuum chamber evacuated by cryogenic pump. The substrates were silicon wafers coated with thermal $SiO_2$. Films grown were of 150 nm thickness. The structural studies made by Reflection High Energy Electron Diffraction have verified that the films grown are polycrystalline, consisting of a mixture of two crystalline phases $VO_2$ and $V_6O_{13}$, and amorphous phase. Sheet resistance of the film measured by four-probe method was 235 kΩ/□. Electrical measurements were carried out on structures made by photolithography. The structure cross section is shown in Fig.1.

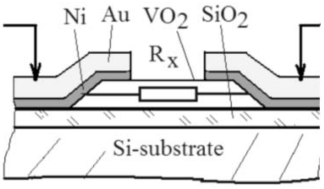

Fig.1. Cross-section of structure.

Contact gap was 3 μm, and the width of the contact area on mesa - 50 μm. Contacts were annealed in quartz reactor tube in a stream of high purity argon at 523K for 30 minutes. Sheet resistance of the film remained almost the same.

The resistance of obtained structure while heated from room temperature (296K) to a temperature of 353K reduced by 4.7 times. Considering that the film was composed of phase mixture, it was assumed that conductive channel of $VO_2$ nanocrystals was missing between the metal electrodes. For creation a conductive channel was used electroforming [7]. To do this, voltage of about 20 – 30 V was briefly applied to a sample through limiting resistance. As the result, conductive channel of about 2 μm width was formed in vanadium oxides films and visualized by atomic force microscopy (Fig.2).

The forming changed the resistance of the structure from 13.4 kΩ to 17.3 kΩ. After forming a structure resistance at heating from room temperature to 353K has decreased by 40.3 times.

I–V characteristics after forming gotten at different temperatures from curve tracer are shown in Fig.3.

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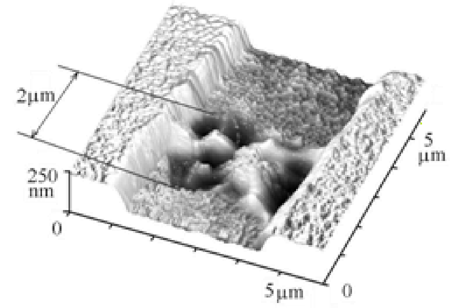

Fig. 2. AFM scan of conductive channel formed by electroforming.

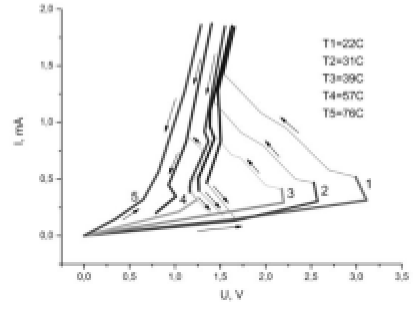

Fig.3. I-V characteristics of the structure with conductive channel at different temperatures.

After forming I-V curves remained stable during measurement process.

It was discovered the phenomenon of stochastic resonance with increasing input signal in the circuit consisting of $VO_2$ structure with conducting channel in series with a resistor. Schematic diagram of the experiment is shown in Fig.4.

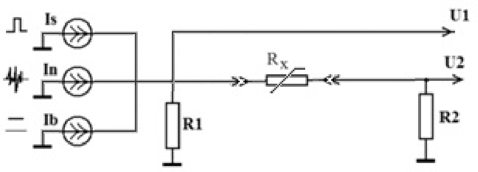

Fig.4. Electric scheme for observation of stochastic resonance in a structure with $VO_2$ conductive channel. Is – input source, In – noise source, Ib – DC source defining operating voltage without signal and noise, R1 = 100 Ω – input resistance, R2 = 1050 Ω – output resistance, Rx = 22.8 kΩ – resistance of the structure, U1– input voltage, U2 – output voltage.

Signal, noise, and dc bias voltage were summed on R1. The signal was a pulse with duration of 1ms, following with frequency of 100 Hz. A noise source generated white noise in the frequency band 10 Hz – 600 kHz.

Input U1 and U2 output voltages were recorded with a digital oscilloscope. Oscillograms of U1 and U2 at different input noise powers, Pnoise, are shown in Fig.5. It can be seen that with increasing noise power signal became insensible on the noise background. There were separate pulses at noise power of about 0.15 mW, showing random film states changing from high to the low-resistance ones. And at the power of 0.29 mW (Fig. 5d) output pulses coincide with input pulses in frequency and phase. The amplitude of output pulses was by 1.6 times higher of input pulses amplitude. With further increasing of the noise power (Fig. 5e) the number of output pulses started to exceed the number of input.

Signal-to-noise ratio at the input (RSN1) and output (RNS2) of scheme were calculated from waveforms of the U1 and U2. The calculation of RSN1 is presented below:

$$RSN1 = U1s^2 / U1n^2 \,;$$

$$(U1n)^2 = \frac{1}{m} \cdot \sum_{j=1}^{m} \frac{1}{T-\tau} \cdot \int_{t_j+\tau}^{t_{j+1}} (U1(t) - \tilde{U}1)^2 \, dt \,;$$

$$\tilde{U}1 = \frac{1}{m} \cdot \sum_{j=1}^{m} \frac{1}{T-\tau} \cdot \int_{t_j+\tau}^{t_{j+1}} U1(t) dt \,;$$

$$(U1n)^2 = \frac{1}{m} \cdot \sum_{j=1}^{m} \frac{1}{T-\tau} \cdot \int_{t_j+\tau}^{t_{j+1}} (U1(t) - \tilde{U}1)^2 \, dt \,;$$

$$(U1s)^2 = \frac{1}{m} \cdot \sum_{j=1}^{m} \frac{1}{\tau} \cdot \int_{t_j}^{t_j+\tau} \left[ \left( U1(t) - \tilde{U}1 \right)^2 - \left( U1n \right)^2 \right] dt \,;$$

$(U1n)^2$ – noise voltage square at the input resistor R1, calculated from oscillogram U1(t) in the time interval ($t_j + \tau$, $t_{j+1}$) without pulses;

$\tilde{U}1$ – DC voltage on resistor R1, calculated by averaging U1(t) in the time interval without pulses;

$(U1s)^2$ – voltage signal square at the input resistor R1, calculated from oscillogram U1(t) in the time interval (tj, tj + τ) with pulses;

t – current time; $t_j$ – the beginning of the j-th pulse;

τ = 1 ms – pulse length;

T = 10 ms – pulse period.

The value of RNS2 was calculated similarly to RNS1.

RSN2(D) dependence (see Fig.6) was obtained by varying power of noise source and calculating the input noise power as

$$D = (Un1)^2 / R1 \,.$$

## IV. MODELING

The MathCAD program was used for modeling stochastic resonance. The scheme of this program model is shown in Fig.7.

A signal ec(t) as rectangular pulses (Fig.8.) and white noise en(t) (Fig.9.) were applied to the input of the nonlinear system (dotted line in Fig.7).

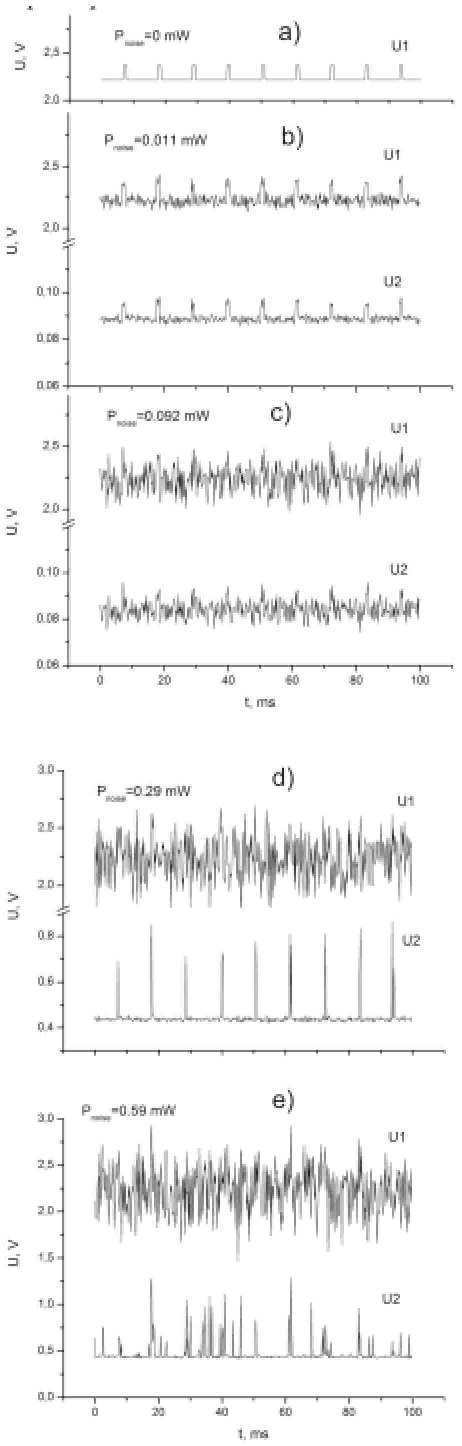

Fig. 5. Oscillograms U1 and U2 at different noise powers at the input, Pnoise.

The signal was an analytic function derived from function f=cos(x) by restricting its values in the intervals. Function en(t) was formed by random number generator with normal distribution. The voltage source Upt set operating voltage to structure without signal and noise. Rogr was limiting resistor.

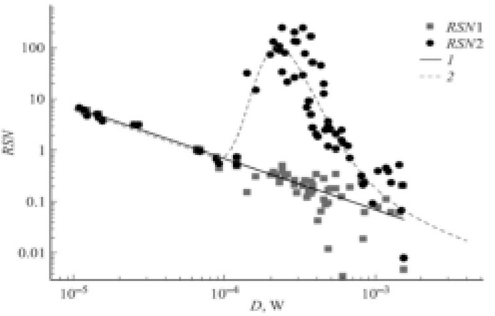

Fig.6. Experimental dependence of signal-to-noise ratio to the noise power D.

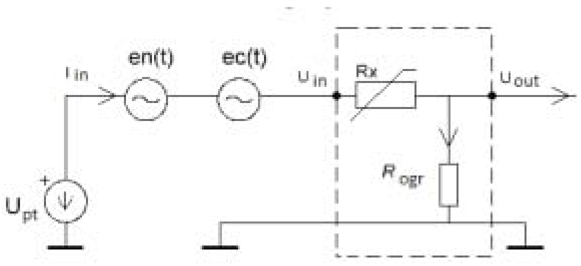

Fig. 7. Scheme of the program model. Upt – DC source voltage; en(t) – noise source voltage; ec(t) – input source voltage; Rx – $VO_2$ thin film; Rogr – limiting resistor; Uout – output signal.

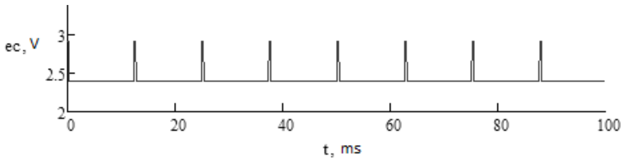

Fig. 8. Plot of source signal ec(t).

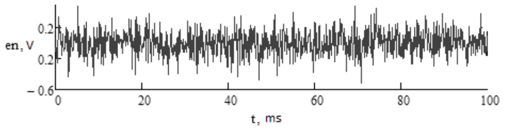

Fig.9. Plot of a Gaussian white noise signal en(t).

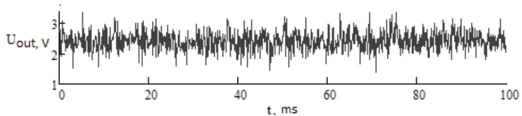

Fig.10. Output signal Uout.

At the system output the resultant signal Uout (Fig.10) was calculated by using following formulas:

$$Uout = Iin \cdot Rogr\,;$$

$$Iin = Ix(Ux)\,;$$

$$Uin = Upt + en + ec\,;$$

The function Ix(Ux) is approximation of experimental current-voltage characteristic (Fig.11), presented in the form of two straight lines (Fig.12) defined by two characteristic points corresponding to experimental I-V curve of film.

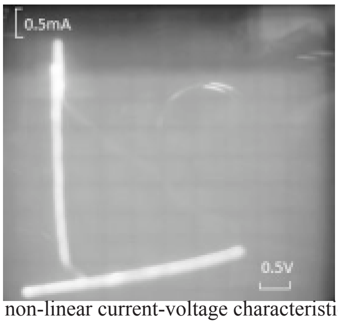

Fig.11. The real non-linear current-voltage characteristics of $VO_2$ film.

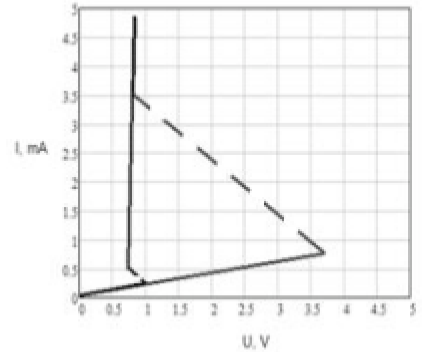

Fig.12. Approximation of experimental current-voltage characteristics.

It was further investigated whether the correlation was between output signal and input signal in presence of noise. For this purpose a dependence of the coefficient of correlation (CC) via noise intensity was determined.

The correlation function was calculated by:

$$Cor(A)=\frac{\sum_{t=0}^{tkn-1}[(ec(t)-ecp)\cdot(Res(t,A)-Rcp)]}{\sqrt{\sum_{t=0}^{tkn-1}(ec(t)-ecp)^2\cdot\sum_{t=0}^{tkn-1}(Res(t,A)-Rcp)^2}},$$

where *tkn* = 100s – time interval of experiment;

*Res*(*t*) – resultant signal obtained by separation of the variable component Us from output signal Uвых according to the formulas:

$$\mathrm{Re}\,s(t)=Uin(t)-Ucp=Us\,;$$

$$Ucp=\sum_{t=0}^{tkn-1}Uout(t)\Big/tkn\,.$$

Mean value of resultant signal Rcp was calculated according to:

$$Rcp=\sum_{t=0}^{tkn-1}Res(t)\Big/tkn\,.$$

The result is shown in Fig.13.

According to the formulas used for calculation of experimental dependencies RNS1 and RNS2, dependence of the signal-to-noise ratio RNSm (Fig.14) was calculated for the model (Fig.7).

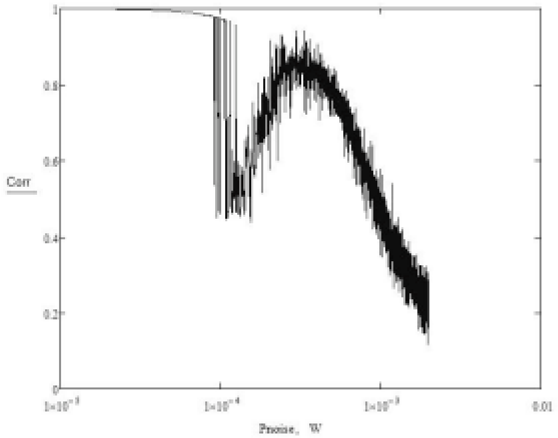

Fig. 13. Correlation function via noise power Pnoise.

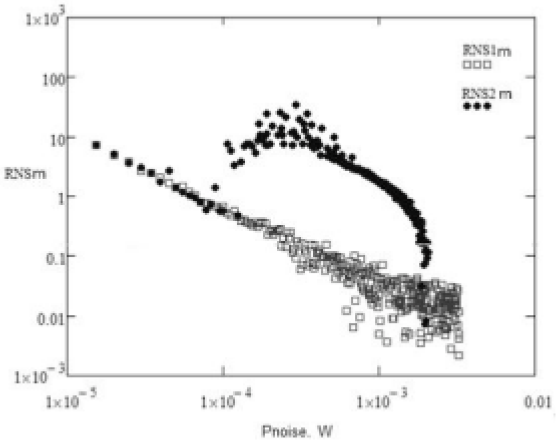

Fig.14. RNS dependences at input and output calculated for the model.

## V. DISCUSSION OF RESULTS

It is seen from Fig.13 that correlation coefficient is nearly equal to 1 at low noise intensity (0.05 mW). At noise intensity of 0.08 mW spontaneous system states changes become possible from semiconductor state to the metallic one leading to sharp increase in internal noise of nonlinear system and decrease of CC. However, CC begins to rise at noise power of 0.1 to 0.3 mW reaching a value of 0.85. This means favorable condition for weak signals detecting for such systems arise at using noise of certain power. This fact can be seen from experimental (Fig.6) and calculated (Fig.14) dependences via input noise power. Calculated dependence of signal-to-noise ratio agrees qualitatively with experimental one. However, experimental dependence increases more rapidly with noise power increasing and quickly subsides after getting at maximum. The difference is probably due to shift of structure operating point by temperature caused by film heating with noise not considered in program.

It is worth mentioning that the dependence RSN2(D) is well described by log-normal distribution with expected value of -0.4 and variance of 0.4. This indicates that response of nonlinear system is multiplicative relative to signal and noise. In part, this explains abnormally high transfer coefficient of signal-to-noise ratio observed in experiment. In fact, harmonic components of signal and noise interact by means of thermal effect in confined space of conductive channel consisting of $VO_2$ film which has abnormally high temperature coefficient of resistance in transition temperature region.

## VI. CONCLUSION

The phenomenon of stochastic resonance was found in vanadium dioxide films.

It was established that vanadium dioxide film enhances signal-to-noise ratio at system output by 250 times at optimal noise intensity, and output signal amplitude can exceed the amplitude of input one by 1.6 times. That is a signal gain in a circuit consisting of only passive elements.

The computer model was suggested to explain experimental dependencies of signal-to-noise ratio via input noise power.

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