The memristor switching behavior from the energy point of view

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Introduction

Since solid-state memristive devices have been fabricated many research centers increased their efforts towards the design of memory and controllable memory blocks using memristors. One of the aspects of switching mechanism in memristive devices is the energy required for the setting and resetting the memristive element. Measurement tests of the self-directed channel (SDC) memristive devices, manufactured by the company Knowm Inc., have been carried out. This device is an ion-conducting memristor comprised of the layered chalcogenide materials Ge2Se3/SnSe/Ag [1].

Reference data measurement

The memristor under study is a self-directed-channel memristor [1] with a tungsten (W) dopant in a 16-pin ceramic DIP package fabricated by the Knowm Inc. To collect the v-i characteristic of the device, the element is connected in series with the resistor $R_s = 6.2\mathrm{k}\Omega$. The main role of the series resistor is to limit the current flowing through the memristor. Limiting the current is necessary to protect the element. Additionally, measuring the voltage over this resistor allows us to obtain the v-i characteristics of the memristor. The series connection is exited by the sine wave with a given amplitude and frequency. We record the applied voltage and the voltage over the resistor R_s, which allows us compute the current flowing through the memristor. The data is collected for several periods of the input signal until the steady state is reached. To create the reference data, we compute the average signal values over the six periods. In these measurements, the current response is on level of some tens of microamperes and a certain level of measurement error can be noticed. The Savitzky-Golay filter [2] is used to filter out high frequencies from the data. From the filtered data $n = 500$ points filling uniformly a single period of the input signal are selected as a reference data for further modeling.

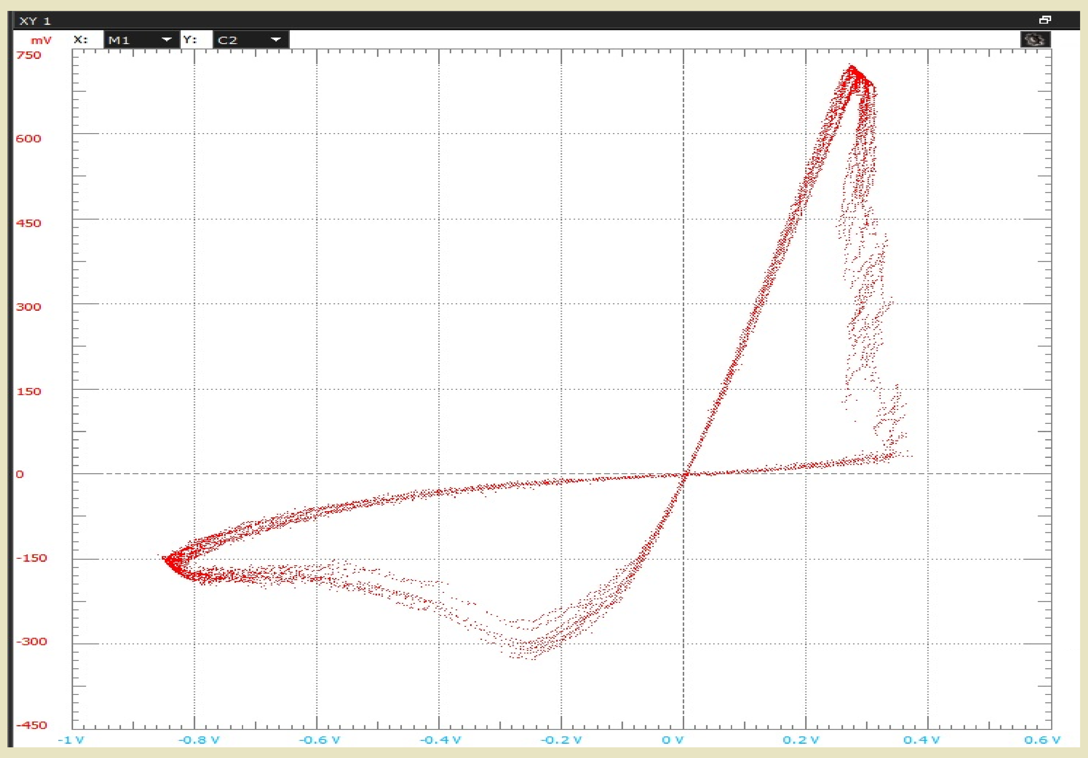


Figure 1: Scope print as an example of measured i-v curve for the reference measurement data collection.

Fitting data to the model

Let $\mathbf{x}$ be the vector of real-valued parameters of a given model and $\mathbf{y}$ be the vectors of integer-valued parameters. The optimization function is defined as

$$F(\mathbf{x},\mathbf{y}) = \frac{1}{n}\sqrt{\sum_{j=1}^{n}\left(i_j(\mathbf{x},\mathbf{y}) - i_{\mathrm{ref},j}\right)^2}, \qquad (1)$$

where n is the number of samples in the reference data, $i_{\mathrm{ref},j}, j \in \{1,2,\ldots n\}$ are the values of the current from the reference data, and $i_j(\mathbf{x},\mathbf{y})$ are the values of the current computed for a given model with parameter values $\mathbf{x},\mathbf{y}$. In the computation, the reference voltage $v_{\mathrm{ref},j}, j \in \{1,2,\ldots n\}$ is applied as the excitation signal. The optimization goal is to find parameter values $\mathbf{x},\mathbf{y}$ minimizing $F(\mathbf{x},\mathbf{y})$. Real-valued and integer-valued parameters are handled in a different way. For fixed values of integer-valued parameters $\mathbf{y}$ finding the optimum values of the real-valued parameters $\mathbf{x}$ is carried out using the *interior-point* algorithm [3] implemented in the MATLAB optimization toolbox. This process is repeated for all admissible combinations of integer-valued parameters. The admissible set for $\mathbf{y}$ is selected by hand. The combination $\mathbf{x},\mathbf{y}$, which leads the the minimal value of the goal function is selected as the solution of the optimization problem.

Reference data

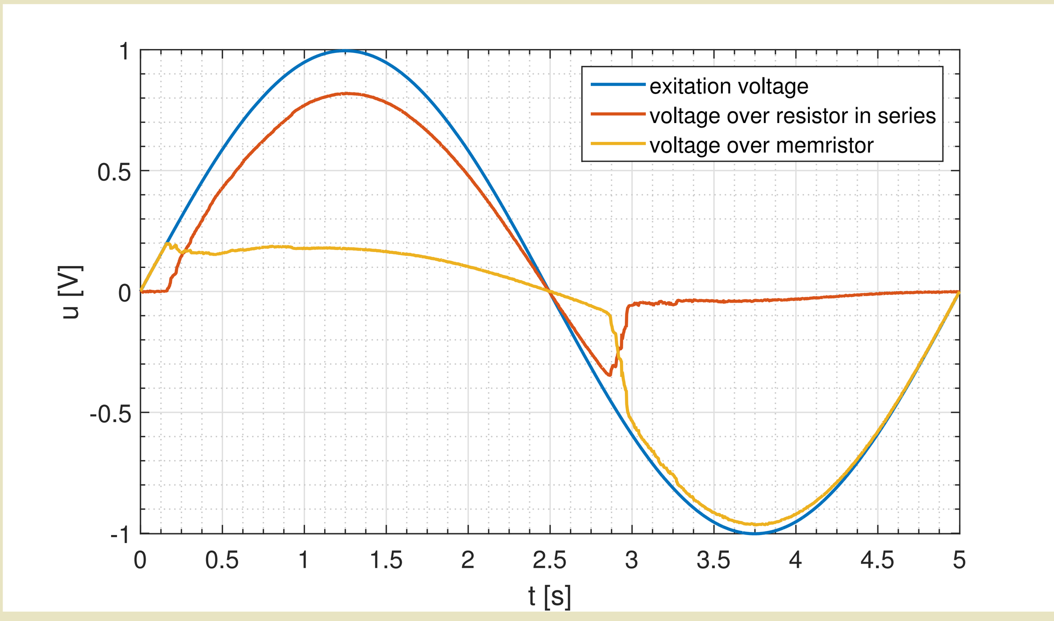
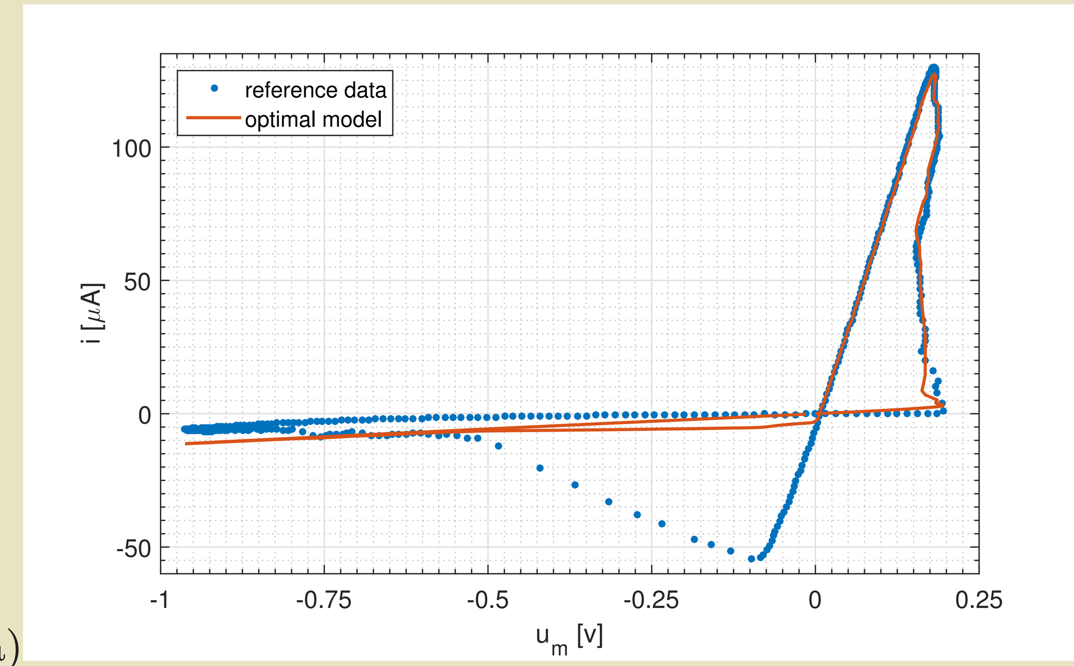


Figure 2: The time response of the memristor and resistor in series for the $v(t) = 1\sin(2\pi f t)$ voltage excitation (average of 6 periods), $f = 0.2$ Hz.

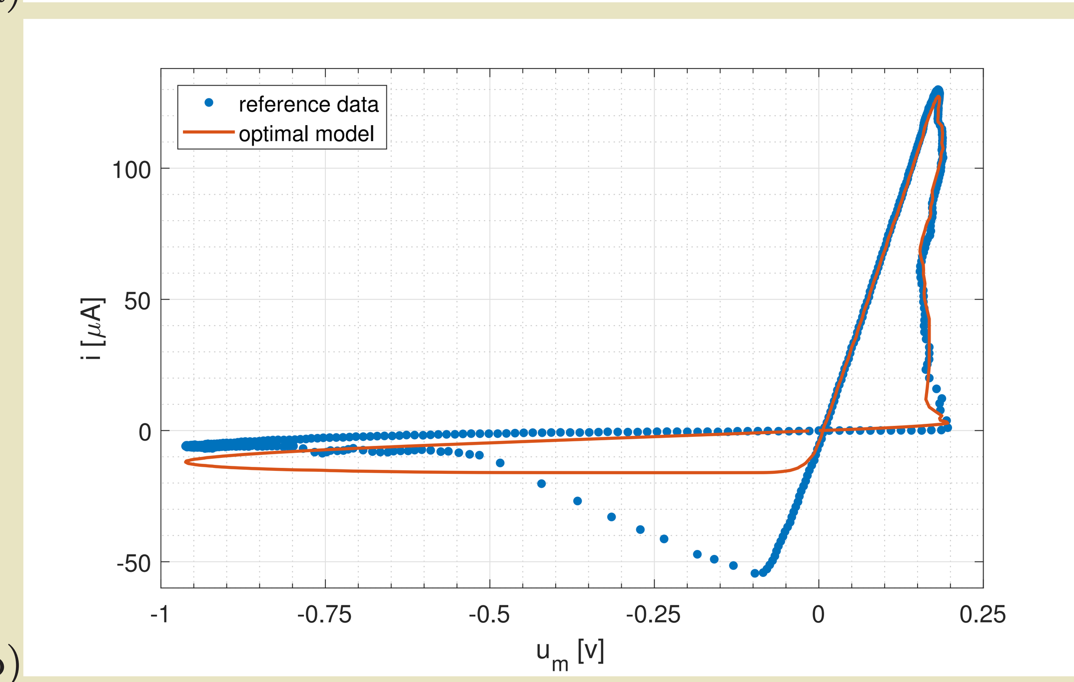
Optimization results

Figures below present the best obtained solutions fit to the data presented in the fig. 2. Author made the optimization procedure using three models.

- Strukov model with Biolek window [4].
- Modified Strukov model with Biolek widow, where two additional parameters are involved.
- VTEAM model [5].



(a)



(b)

Figure 3: The Strukov model with Biolek window fitted to the reference data. a) simple Strukov model with biolek window. b) modified Strukov model with Biolek window

The optimal model parameters are:

- simple Strukov - $p = 2$, $\mathcal{R}_{\mathrm{ON}} = 1558\ \Omega$, $\mathcal{R}_{\mathrm{OFF}} = 82.7\ \mathrm{k}\Omega$, $k = 779$, and $F(\mathbf{x},\mathbf{y}) = 0,04102$.
- modified Strukov - $(p_{\mathrm{ON}}, p_{\mathrm{OFF}}) = (1,30)$, $\mathcal{R}_{\mathrm{ON}} = 1551\ \Omega$,, $\mathcal{R}_{\mathrm{OFF}} = 102.73\ \mathrm{k}\Omega$, $k_{\mathrm{ON}} = 1597$, $k_{\mathrm{OFF}} = 27$, and $F(\mathbf{x},\mathbf{y}) = 0,01023$.

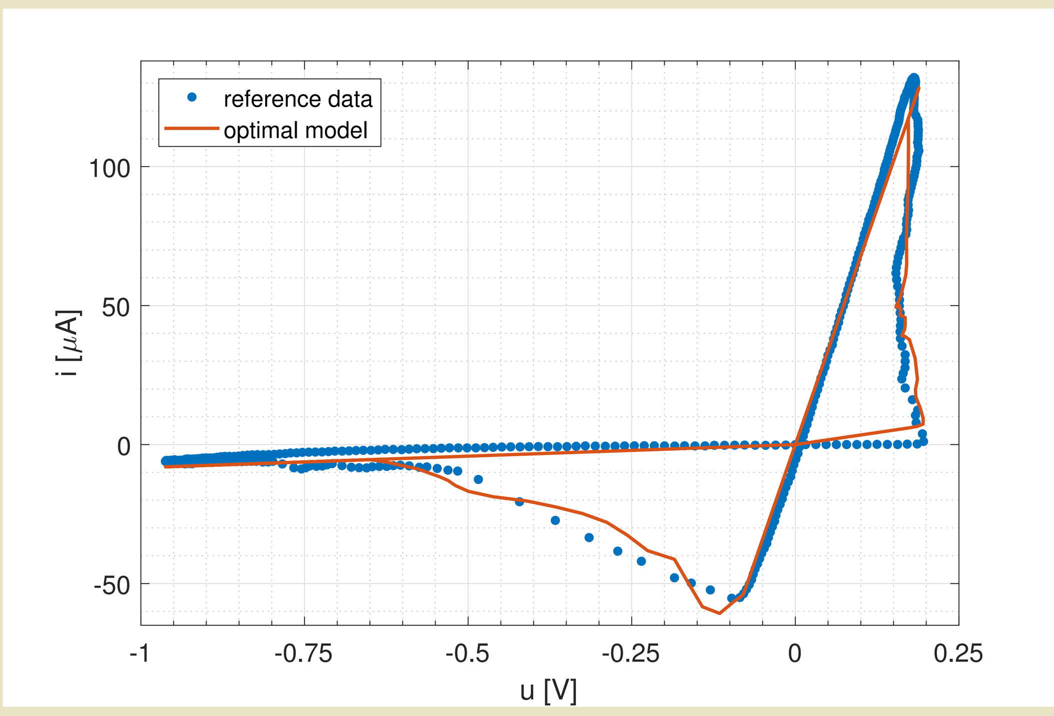


Figure 4: The best VTEAM fit to the reference data.

The optimal model parameters are:

- VTEAM - $(\alpha_{\mathrm{ON}}, \alpha_{\mathrm{OFF}}) = (12,1)$, $\mathcal{R}_{\mathrm{ON}} = 1471.797\ \Omega$, $\mathcal{R}_{\mathrm{OFF}} = 12\ \mathrm{k}\Omega$, $w_{\mathrm{ON}} = 0.2073$, $w_{\mathrm{OFF}} = 0$, $w_{\mathrm{init}} = 0$, $v_{\mathrm{ON}} = 96$ mV, $v_{\mathrm{OFF}} = -96$ mV, $k_{\mathrm{ON}} = 3.050$, $k_{\mathrm{OFF}} = 0.7511$ and $F(\mathbf{x},\mathbf{y}) = 0,00201$.

The best fit to the reference data is achieved using the VTEAM model [5].

Power and energy calculation

The resistance changes during the sinusoidal excitation. Figure 5 presents the resistance change over the time. Using this phenomenon one can assume the time when memristor switched from the OFF to ON state while was treated with the positive voltage, and similarly from the ON to OFF state while the voltage was negative.

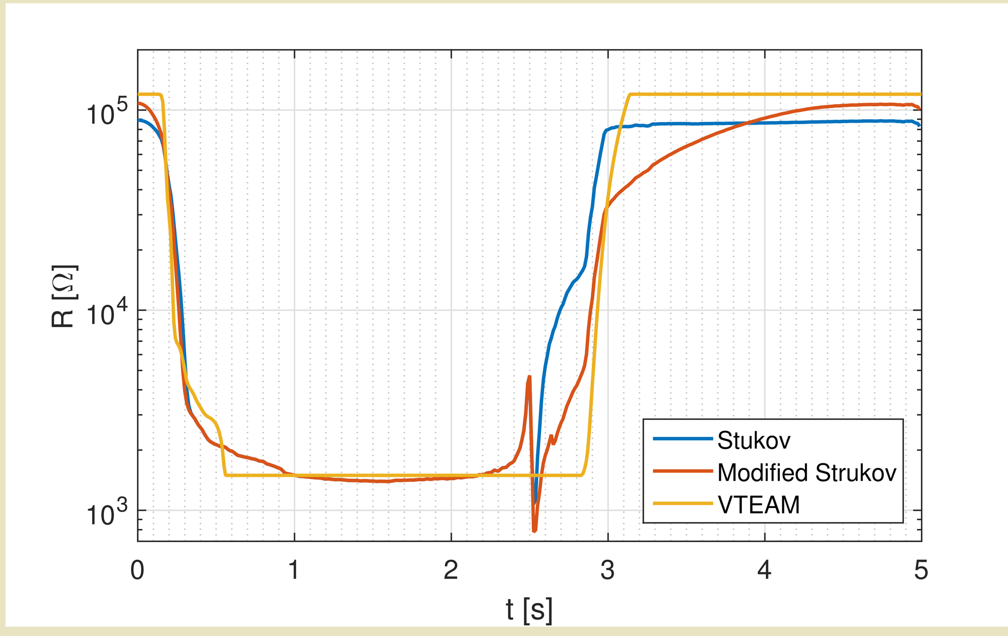


Figure 5: Resistance of the memristor over the time.

The power function over the time $p(t) = u \cdot i$ while switching the memristor state has been presented on the fig. 6. The power function describes the speed of energy dissipation in the element.

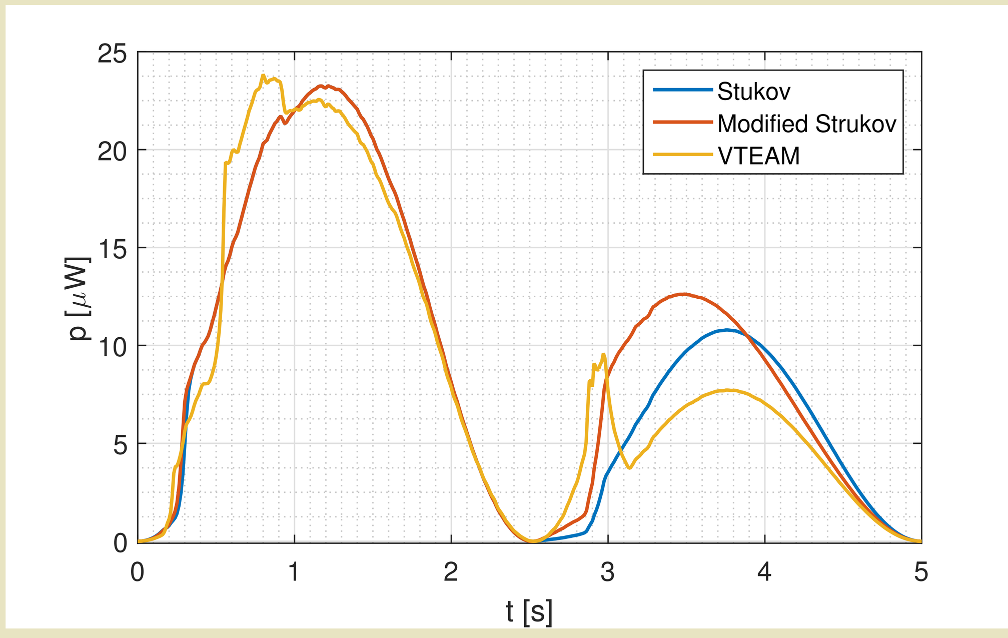


Figure 6: Power function $p(t) = u \cdot i$ over the time

Assuming the time needed the memristor to change the state one can assume the energy required for the switching, as an integral over the $p(t)$ function in the certain time interval $[t_1, t_2]$.

Switching direction	Model	t_1 [s]	t_2 [s]	Energy [μJ]
OFF → ON	Strukov	0	0.988	10.991
	Strukov 2	0	0.988	11.118
	VTEAM	0	0.560	2.687
ON → OFF	Strukov	2.5	3.04	0.464
	Strukov 2	2.5	3.92	7.211
	VTEAM	2.5	3.14	2.398

Conclusions

Several existing memristor models have been fitted to model the behavior of a self-directed-channel memristor with tungsten dopant. It has been shown that the VTEAM model outperforms the other models considered. The standard Strukov model with Biolek window cannot be successfully used for modeling of this device because the process of memristor switching is different for different voltage polarization. A modified version of the Strukov model has been proposed which overcomes these difficulties. It has been shown that the modified model provides much better fitting to the measurement data than the original model. As the VTEAM model is the most accurate the energy needed to switch the memristor for its barriers states can be estimated to the level of $2 \div 3\,\mu$J.

References

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