Program for evaluation of the 3ω results

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To evaluate the 3ω data run the file *Dialog3w.m.*

1 General information

1.1 Names of the files

- file with 3ω results: SampleName_PowermW_U3w.dat (e.g. DSO-NSTO-500p_15mW_U3w.dat)
- file with dRdT data: SampleName_dRdT.dat (e.g. DSO-NSTO-500p_dRdT.dat)
- file with current, voltage and relative width of the heater: SampleName_PowermW_VIP.dat (e.g.DSO-NSTO-500p_25mW_VIP.dat)
- images: SampleName_0x.png (e.g. DSO-NSTO-500p_01.png)

1.2 Structure of the files

1. File with 3ω results (data in μV):

f(Hz)	Sample1	Sample2	Sample3	Sample4 //structure
	DSO–NSTO	empty	empty	DSO–Substrate
100	1211.77002	NaN	NaN	1133.449951
116	1164.210083	NaN	NaN	1090.650024
135	1118.910034	NaN	NaN	1047.97998
157	1073.01001	NaN	NaN	1006.369934
183	1027.710083	NaN	NaN	963.4530029
212	984.5569458	NaN	NaN	923.756958
247	940.5650024	NaN	NaN	882.1519775
287	897.6500244	NaN	NaN	842.4559937
333	855.9260254	NaN	NaN	803.473999
387	814.7990112	NaN	NaN	764.7310181
450	774.1490479	NaN	NaN	726.4650269
523	734.690979	NaN	NaN	689.2720337
608	696.0670166	NaN	NaN	652.9130249
707	658.3969727	NaN	NaN	617.5079956
822	621.6799927	NaN	NaN	583.2949829
955	586.7520142	NaN	NaN	550.1550293
1110	552.7770386	NaN	NaN	518.2069702
1291	520.1139526	NaN	NaN	487.4490051
1500	489	NaN	NaN	458.1229858
1744	458.9580078	NaN	NaN	429.9899902
2027	430.3469849	NaN	NaN	403.0480042
2356	403.2870178	NaN	NaN	377.5379944
2739	377.5379944	NaN	NaN	353.4570007
3183	353.3379822	NaN	NaN	330.8079834
3700	330.4500122	NaN	NaN	309.4689941

if you have 2 samples instead of 4, it is necessary to write NaNs in 2 columns so these columns will not be taken into account while calculation.

Important!

- Column 1: frequency (Hz)
- Columns 2-3: thick films ($U_{3\omega}$(μV))
- Columns 4-5: reference films ($U_{3\omega}$(μV))

2. File with dRdT data (data must be in Ohm!):

Pt100	Sample1	Pt100	Sample2	Pt100	Sample3	Pt100	Sample4
Pt100	S1	empty	empty	empty	empty	Pt100	Substrate
107.13	24.84	NaN	NaN	NaN	NaN	107.12	23.66
109.75	25.19	NaN	NaN	NaN	NaN	109.76	23.99
111.22	25.39	NaN	NaN	NaN	NaN	111.24	24.20
112.46	25.56	NaN	NaN	NaN	NaN	112.48	24.36

The data saved in the files from dRdT data acquisition is measured voltage in mV. The current applied during the measurement is 100 μA. Therefore, to get the resistance in Ohm one has to multiply the measured data by 10. Additionally, in the SampleName_dRdT_measured.dat file the measurements for positive and negative current are saved. Therefore, it is necessary to calculate an average from both entries - first(third...) line corresponds to a measurement for +I whereas second(fourth...) line is V measured for -I.

Important!

- Columns 1-4: thick films (R (Ω))
- Columns 5-8: reference films (R (Ω))

3. File with current and voltage used during the 3ω measurement and relative width of the heater:

Quantities	Sample1	Sample2	Sample3	Sample4	//structure
	DSO–NSTO	empty	empty	DSO Substrate	
Uappl(V)	3.971999884	NaN	NaN	4.427999973	
Uw(V)	0.819400012	NaN	NaN	0.800800025	
Iw(mA)	30.52700043	NaN	NaN	31.22599983	
Pixel	0.93025	NaN	NaN	0.94458	

Important!

- Column 1: names of the quantities
- Columns 2-3: thick films
- Columns 4-5: reference films

Uappl (V), Uw (V), Iw (mA) are saved during the 3w measurement. Quantity called "pixel" is a relative heater width that is determined by the subprogram called "HeaterWidth". It is width of a heater on a given sample (in pixels) divided by the width of a heater on a mask (also in pixels). The width of mask for 20 μm structure is saved in the program.

2 Subprogram HeaterWidth

There are two main layouts of this program - designed for single samples (Layout/Single samples) and for a series of samples (Layout/series of samples). The second variant is default.

The program works in the following way: the user specifies two points on one side of the heater line that create a line. In the second step the user chooses several points (e.g. 5) on the opposite edge and the program calculates a distance between the line and these points and calculates an average. In Single samples mode this is the outcome of the analysis. In Series of samples mode the final result is an average of e.g 5 points per image and a given number of images (e.g. 3), so in total there are 15 heater widths to be taken to the average calculation.

The outcome of the program is a relative heater width - it is width of the heater on the given sample (in pixels) divided by the width of the heater on a mask (also in pixels). The width of mask for 20 μm structure is saved in the program.

2.1 Single samples:

- Pressing on buttons Sample 1, Sample 2, etc. you choose the files you want to measure.
- Specify number of points to be measured - how many measurements do you want to take for every line and press OK button. If you choose for example 5, then a program calculates an average of the 5 measurements and gives you a mean value as an outcome.
- When you are done with choosing the points the result will show up in the small table.You can save the data pressing Save button.

2.2 Series of samples:

- Specify the folder where the data for thick and reference samples are saved.
- Filenames for images should have form SampleName_01.png. In a field next to "Sample" label you have to write SampleName and specify how many images are saved in a series. E.g. if you have S1_01.png, S1_02.png, S1_03.png and S1_04.png, you write "S1" next to label "Sample 1" and "4" next to "No. of images".
- If you have only 2 series of samples to measure that are in the same directory, you have to specify only the path to "Thick samples", however, if you have 4 series of samples, you have to specify "Ref. samples" path as well. Even if all the images are in one folder you have to specify the path twice.

3 Subprogram Dialog3ω

- Specify the directory that contains your data. Pay attention to the filename pattern that was described at the beginning of this document (section 1.1).
- Insert your SampleName and Power - based on this information the program will be able to find your files.
- Insert the thickness of your sample - the difference in thickness between thick and the reference samples.
- Specify the dimensions of a heater structure that you use. Be careful! The program asks you for b, not 2b - if total width of your heater line is 2b = 20 μm, you have to insert b = 10 μm.

- You can save your results in .png or/and .pdf files. Three files will be saved:
  - dRdT fit,
  - fit of the $U_{3\omega}$ for slope based method and the determination of substrate thermal conductivity,
  - temperature oscillations for every sample and the difference between temperature oscillations for thick and reference samples
- additionally program generates also .xlsx (Excel) file containing summary of all the calculated data.

4 Governing equations

- $P = U_\omega \cdot I_\omega$
- $R = \frac{U_\omega}{I_\omega}$
- $\frac{dR}{dT} = \frac{dR_{hester}}{dT} = \frac{dR_{Pt100}}{dT} \cdot \frac{dR_{heater}}{dR_{Pt100}} = 0.390802\,\frac{\Omega}{K} \cdot \frac{dR_{heater}}{dR_{Pt100}}$
- Thermal conductivity of the substrate - calculated based on a slope method

$$\kappa_{substrate} = \frac{U_\omega^3}{4\pi l R^2} \frac{1}{\frac{d(U_{3w})}{d(ln 2\omega)}} \frac{dR}{dT}$$

- Temperature oscillation introduced to the sample

$$\Delta T = 2 \frac{1}{\frac{dR}{dT}} R \frac{U_{3\omega}}{U_\omega}$$

- Considering a heat flow analogously to an electric current, one can write an analogy to the Ohm's law.

$I = \frac{U}{R} = \frac{\sigma S}{L} U$	$Q = P = \frac{\kappa_{TF} \cdot 2b \cdot l}{d_{TF}} \Delta T_{TF}$
σ	κ
S	$2b \cdot l$
L	film thickness d_{TF}
U	ΔT_{TF}

where $d_{TF} = d_{thick\,film} - d_{reference}$ and $\Delta T_{TF} = \Delta T_{thick\,film} - \Delta T_{reference}$, $2b$ is the heater line width and l is its length between the voltage pads, P is the power used for a measurement. Based on the comparison presented above, thermal conductivity of the thin film may be calculated according to

$$\kappa_{TF} = \frac{P \cdot d_{TF}}{2b \cdot l \cdot \Delta T_{TF}}$$