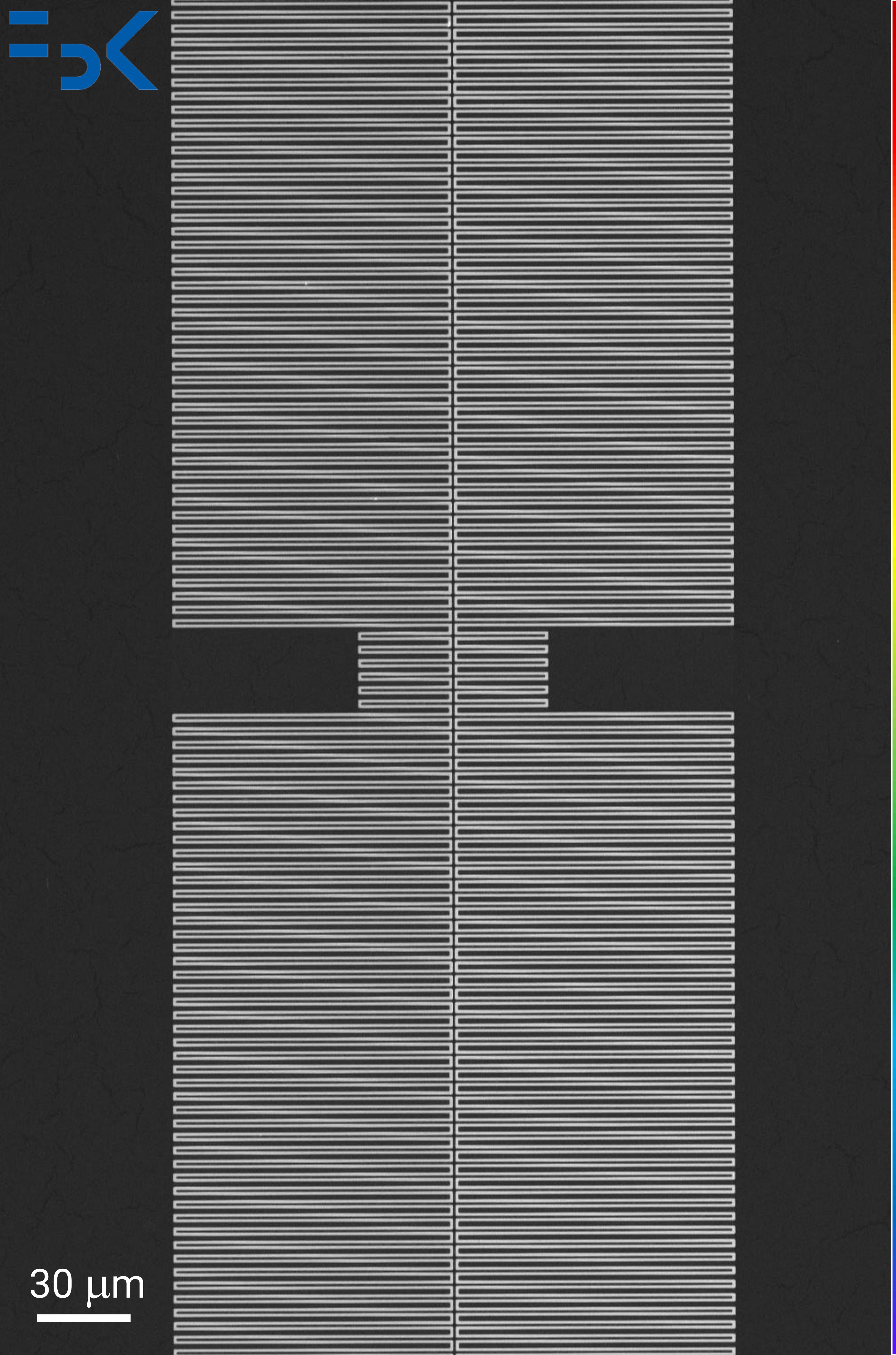


DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

Fabrication and characterisation of high kinetic inductance NbTiN films

DART WARS Collaboration Meeting
6 February 2023

Federica Mantegazzini

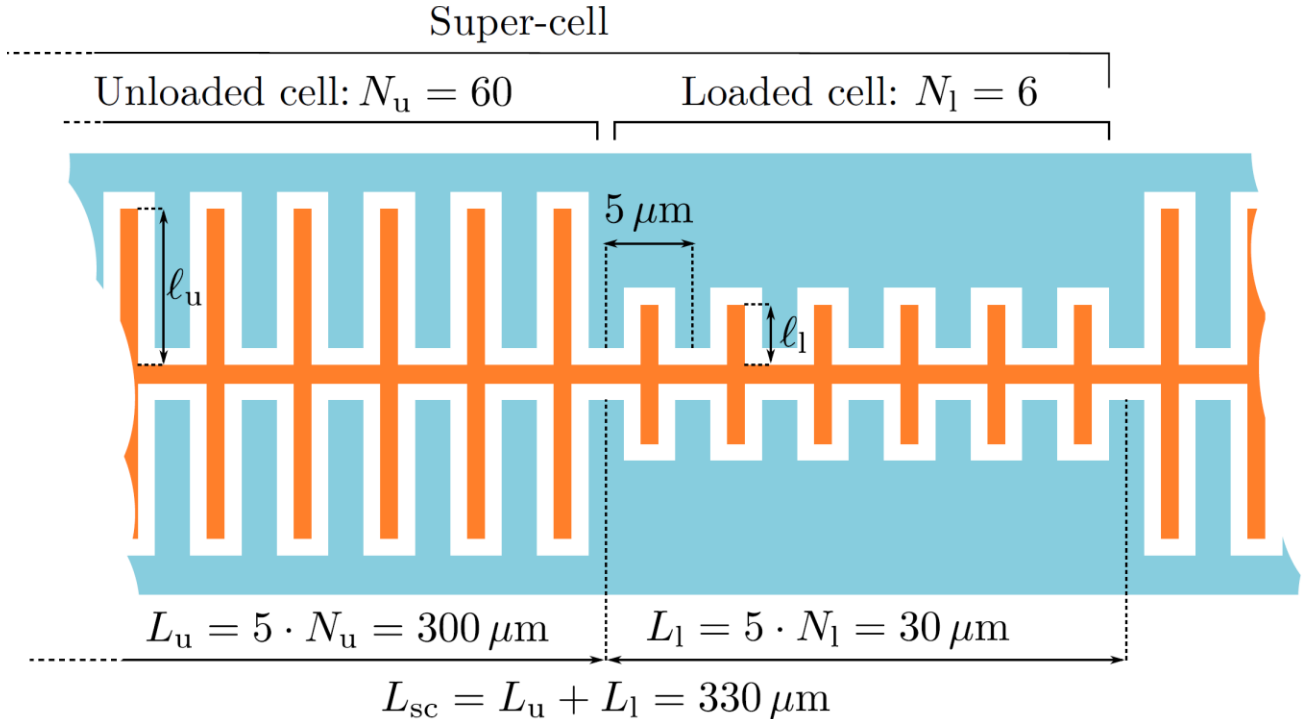
Roadmap

Goal: Definition of deposition recipe for high kinetic inductance and highly non linear superconducting films for TWPAs

→ high R_S, sufficiently high T_c, control on L_0

Steps:

1. Choice of the material
2. Exploration of the sputtering parameters
3. Fine-tuning of the deposition recipe
4. Measurement of the kinetic inductance
5. Fabrication of first KI-TWPA prototypes



$$L_K(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

$$I_* \propto 1/\sqrt{R_n}$$

$$Z_0 = \sqrt{L_d/C}$$

(see Andrea Giachero's presentation)

1. Choice of the material

In order to reach high parametric amplification

→ fabricate a sufficiently non-linear low-dissipative medium with feasible length

→ maximise the non-linearity of the kinetic inductance:

$$L_K(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right) \quad \text{with} \quad I_* \propto 1/\sqrt{R_n}$$

→ Best material candidates: high-resistivity superconductors

Our choice: **NbTiN** → high resistivity (o.f.m. 100-200 μΩcm)

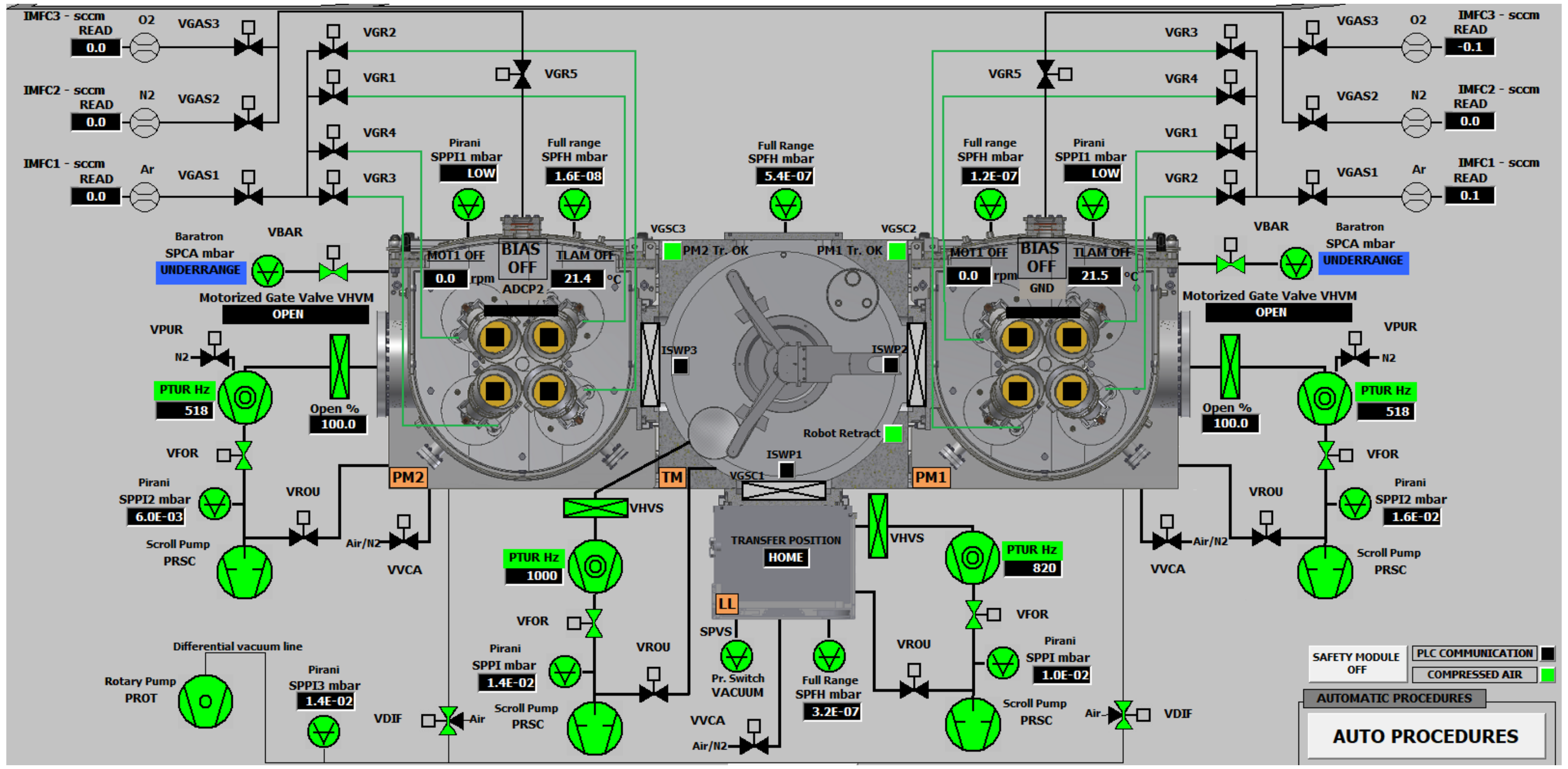
→ high critical temperature (~ 12-13 K)

2. Exploration of the sputtering parameters

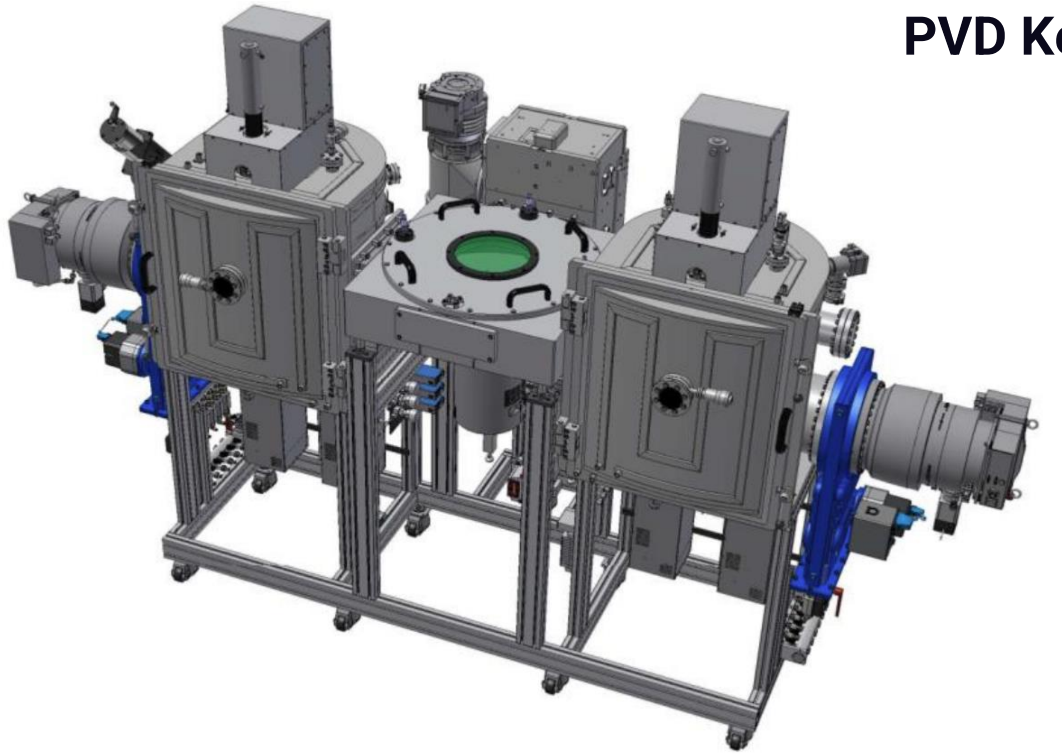
- Load-lock chamber + 2 deposition chambers
- Vacuum ~1e-8 mbar
- Upwards sputtering
- $Nb_{80\%}Ti_{20\%}$ target

Example of recipe for NbTiN films:

Parameter	Typical values
Power (P)	500-1000 W
Pressure (p)	1-5e-3 mbar
Ar flow (f_{Ar})	50 sccm
N_2 flow (f_{N2})	3-10 sccm
Chuck temperature (T)	200-500 °C
Deposition time (t)	2-10 minutes



PVD Kenosistec 800 C



2. Exploration of the sputtering parameters

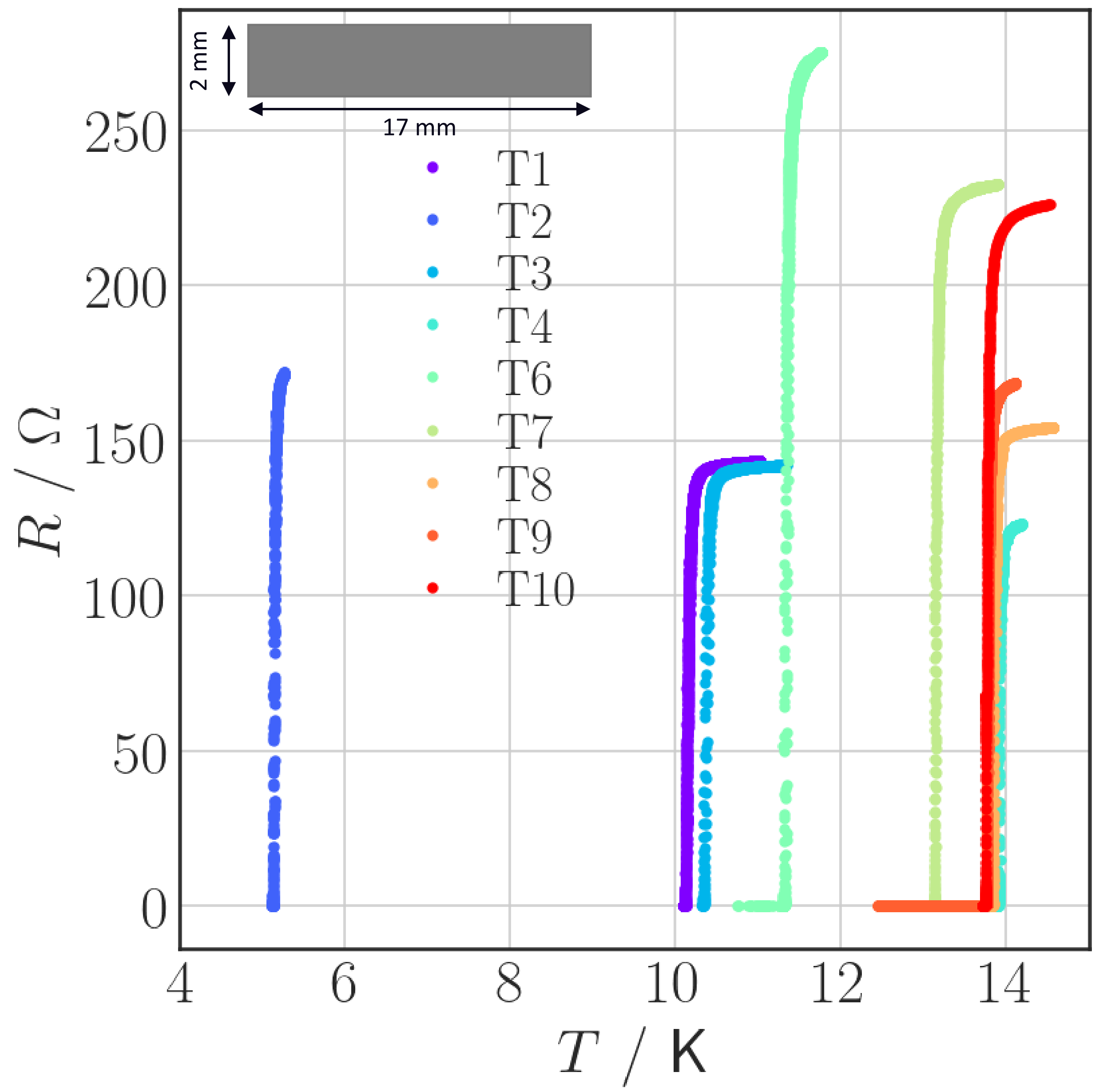
Run *R1*: Blank wafers diced in samples → transition measurements in liquid helium (T = 4.2 K)

Fabrication run *R1*				
Wafer	P/W	p/mbar	f_{Ar}/sccm	f_{N_2}/sccm
T1	700	2e-3	50	5
T2	700	3e-3	50	4
T3	700	3e-3	50	5
T4	700	3e-3	50	6
T5	1200	3e-3	50	5
T6	700	3e-3	50	7
T7	700	3e-3	50	8
T8	700	3e-3	50	6.5
T9*	700	3e-3	50	7
T10	600	3e-3	50	7

*T = 300 °C

Deposition time fixed at t = 6 minutes

Note: deposition rate depends on P, p, f_{Ar}/f_{N2}
→ film thickness is not constant



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Run *R1*: Blank wafers diced in samples → transition measurements in liquid helium (T = 4.2 K)

Fabrication run *R1*							
Wafer	P/W	p/mbar	f_{Ar}/sccm	f_{N_2}/sccm	T_c/K	R_s/Ω/sq	L_0/pH/sq
T1	700	2e-3	50	5	10.16	17.88	2.43
T2	700	3e-3	50	4	5.15	21.5	5.77
T3	700	3e-3	50	5	10.38	17.75	2.36
T4	700	3e-3	50	6	13.9	15.63	1.55
T5	1200	3e-3	50	5	$<$4.2	-	-
T6	700	3e-3	50	7	14.17	19.63	1.91
T7	700	3e-3	50	8	13.16	29.75	3.12
T8	700	3e-3	50	6.5	13.86	19.25	1.92
T9*	700	3e-3	50	7	13.86	19.25	1.92
T10	600	3e-3	50	7	13.77	21.13	2.12

$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$

$^*T = 300\,^{\circ}\mathrm{C}$

2. Exploration of the sputtering parameters

Run *R1*: T_c, R_S, L_0 as function of nitrogen flow

L_0 is estimated as $L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$

Fabrication run *R1*				
Wafer	P/W	p/mbar	f_{Ar}/sccm	f_{N_2}/sccm
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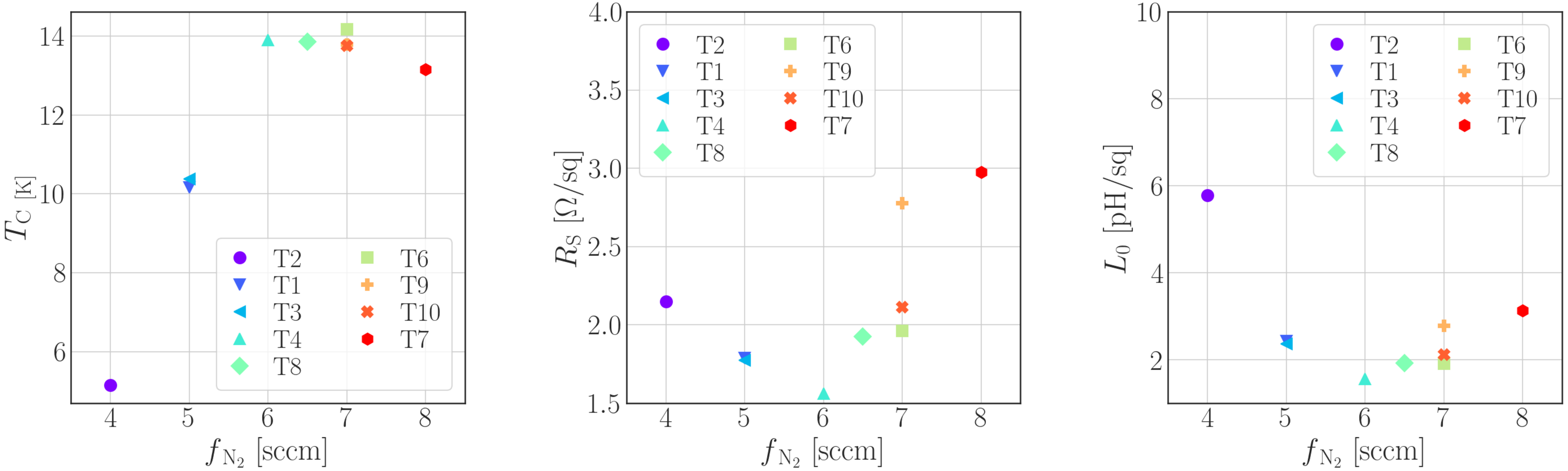

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Run *R1*: T_c, R_S, L_0 as function of nitrogen flow

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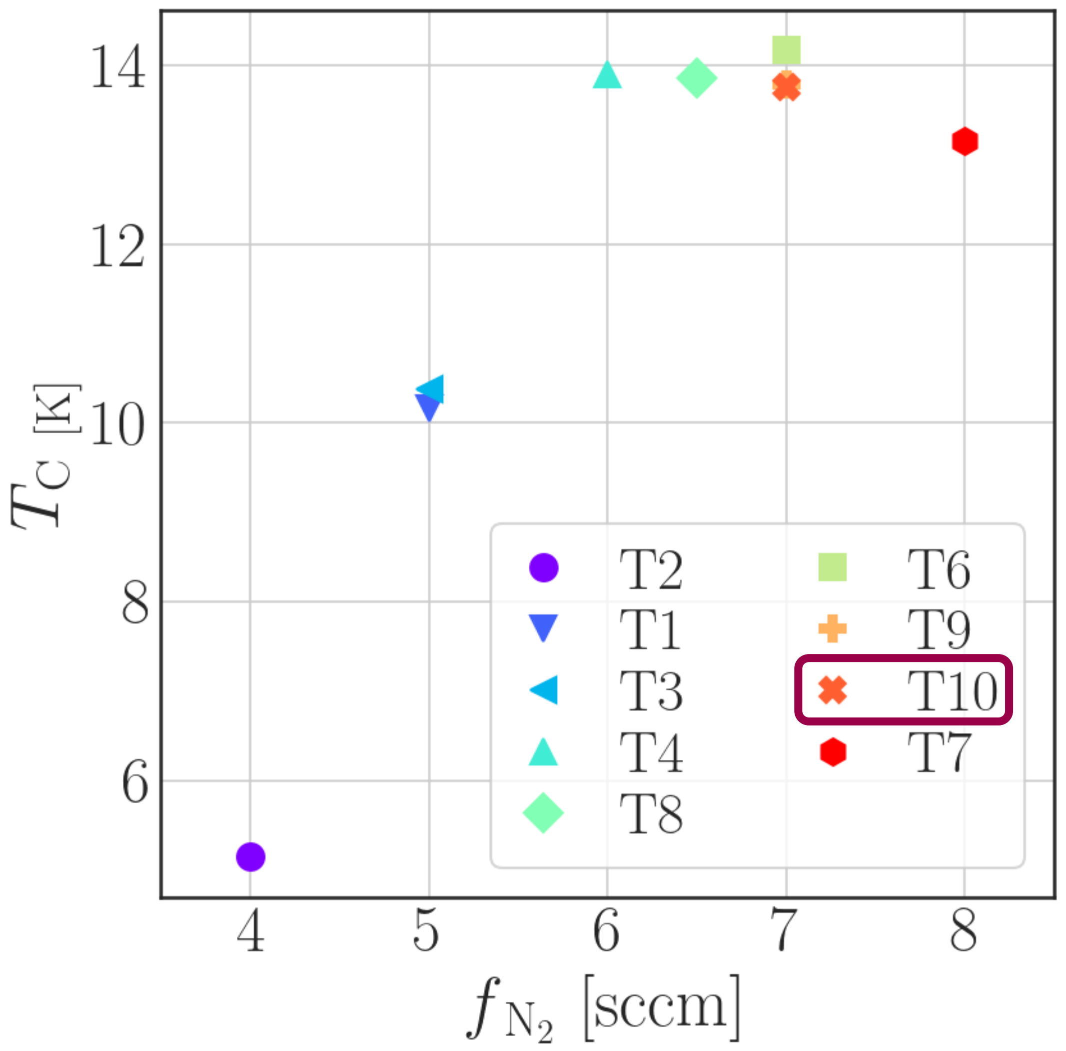
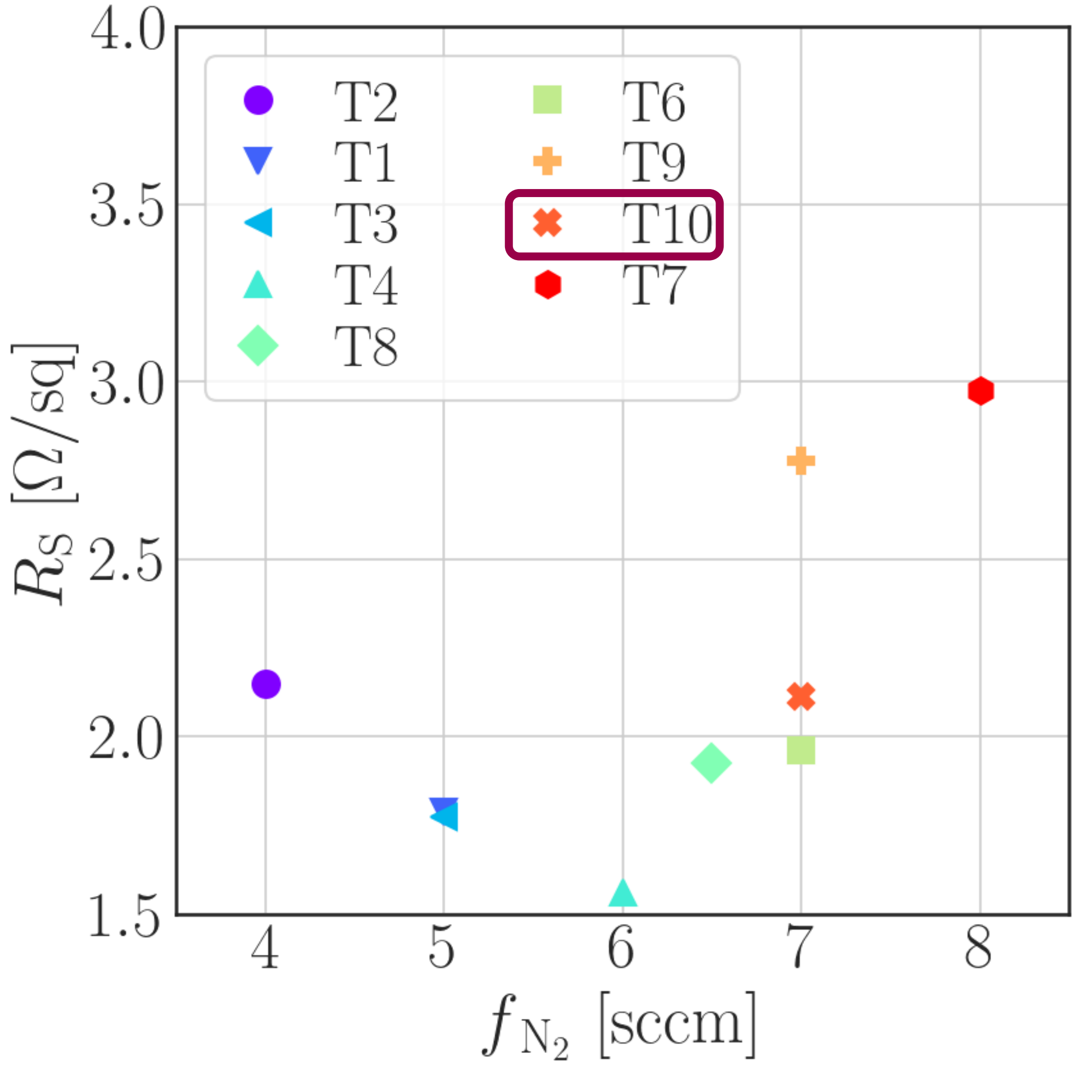
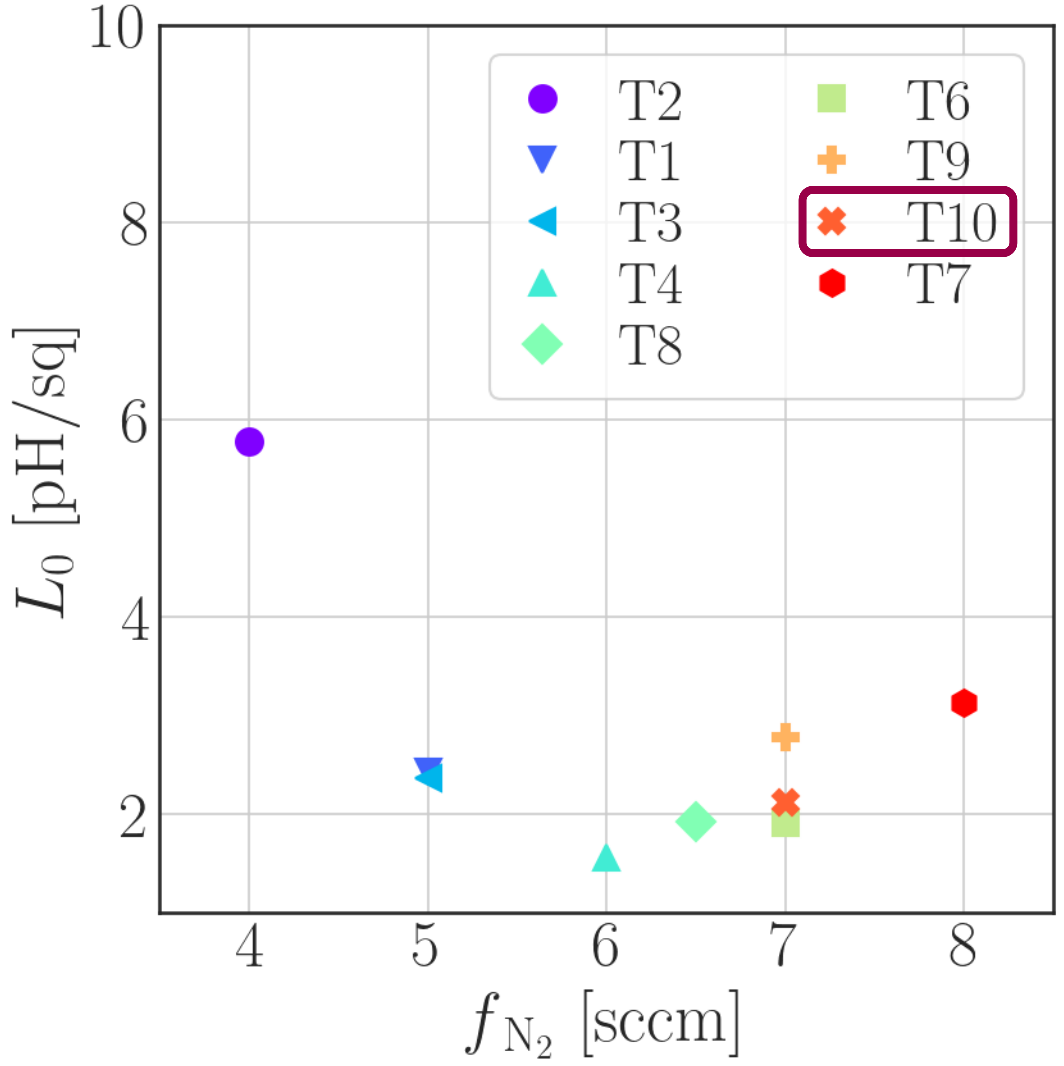






→ Recipe T10: high T_c and sufficiently high R_S

3. Fine-tuning of the deposition recipe

Fixed parameters:

→ *constant deposition rate*

Parameter	Value
Power (P)	600 W
Pressure (p)	3e-3 mbar
Ar flow (f_{Ar})	50 sccm
N_2 flow (f_{N2})	7 sccm
Chuck temperature (T)	400 °C
Deposition time (t)	4 minutes

Varying time: $t \in$ [2, 9 minute]

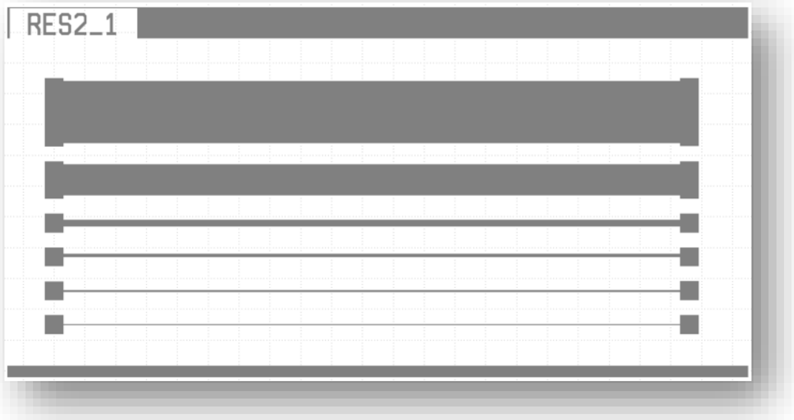
→ *varying thickness*

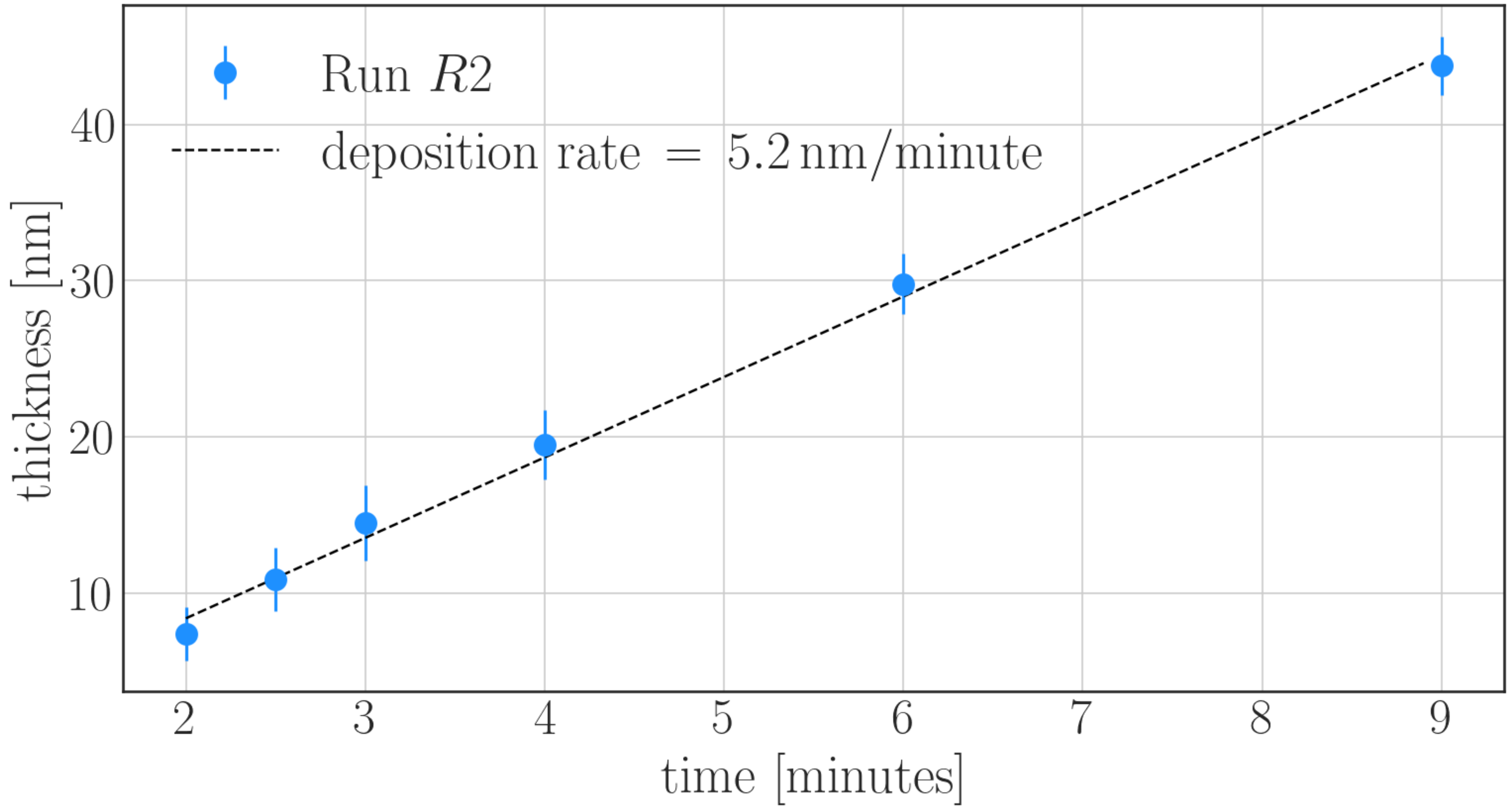
Fabrication run *R2*	
Wafer	t/minutes
W1	6.0
W2	2.0
W3	9.0
W4	4.0
W5	3.0
W6	2.5

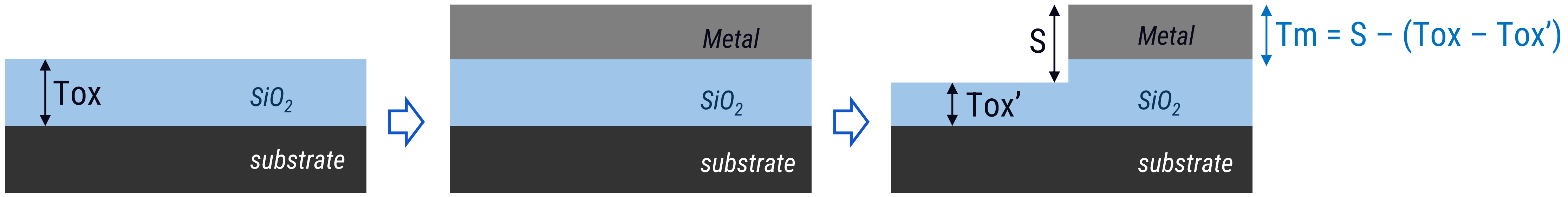
3. Fine-tuning of the deposition recipe: Sputtering rate

Calibration of sputtering rate

→ Lithography step is necessary to precisely measure the metal thickness:







Note: Oxide thickness measured with optical interferometer
Metal thickness measured with AFM

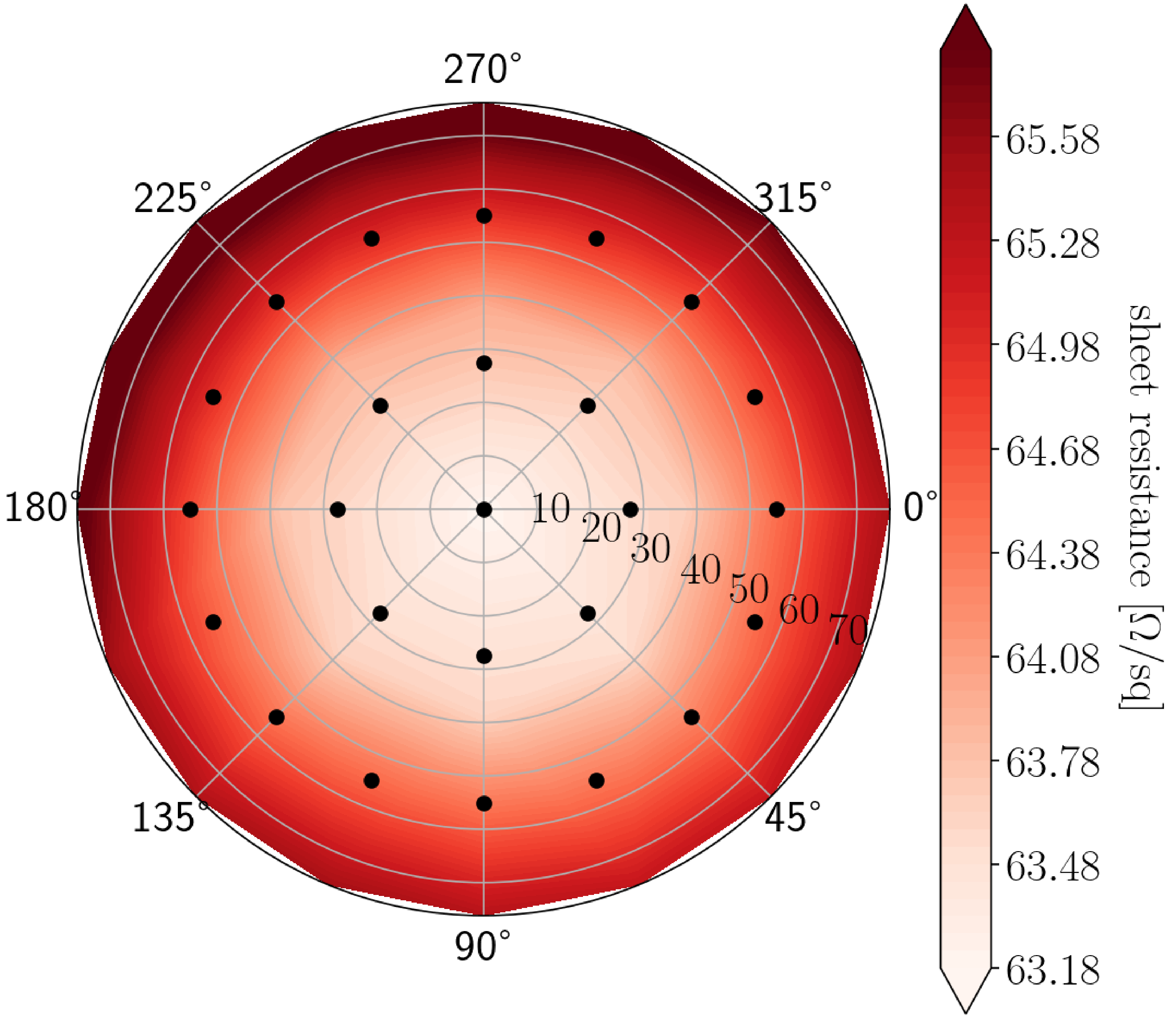
3. Fine-tuning of the deposition recipe: Uniformity

Estimation of the uniformity of the film thickness

→ Measurement of the sheet resistance
(25 points over the 6 ″ wafer)

→ Variation is about 4%

→ Radial gradient (thinner film at the edge)



3. Fine-tuning of the deposition recipe

Fixed parameters:

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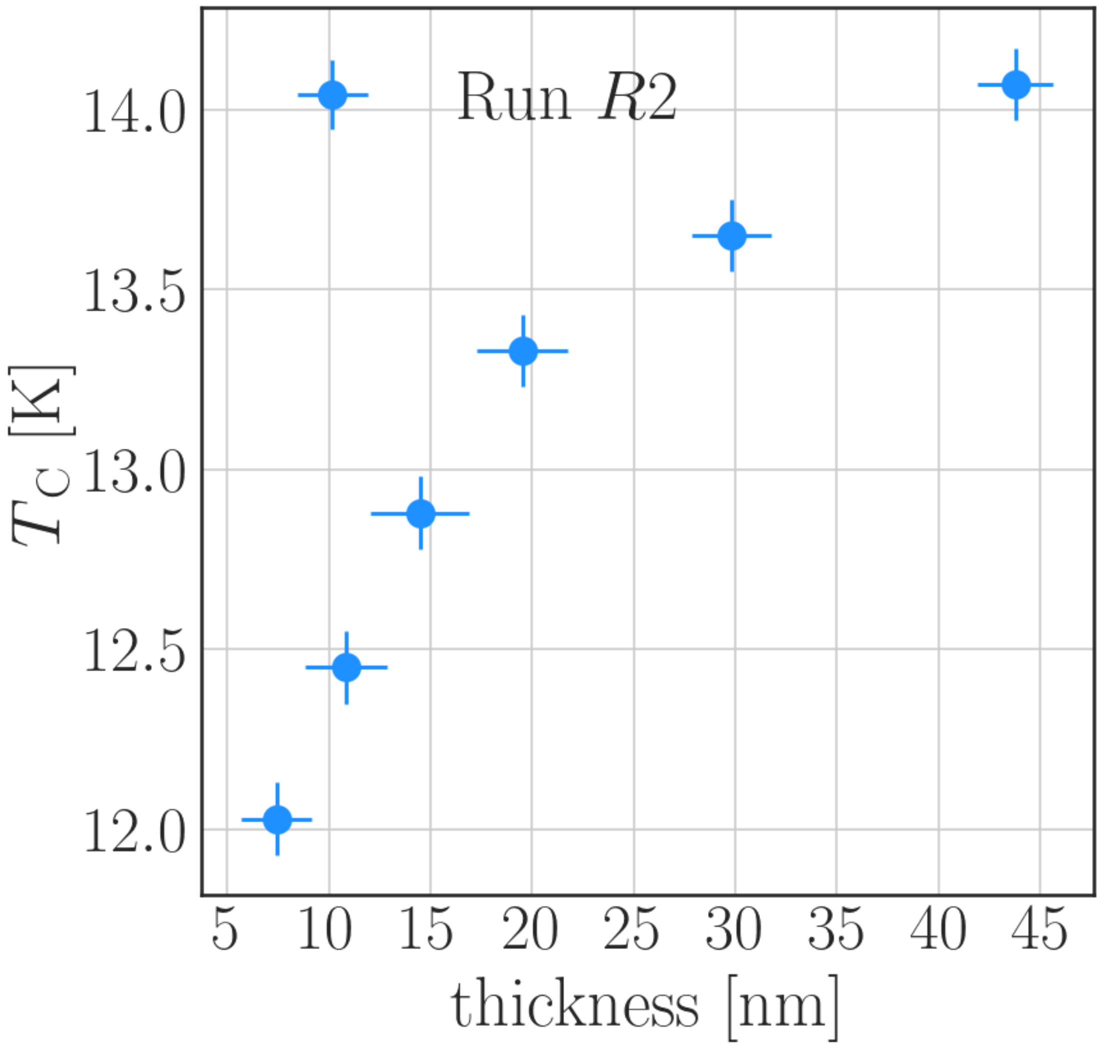
Pressure (p)	3e-3 mbar
Ar flow (f_{Ar})	50 sccm
N_2 flow (f_{N2})	7 sccm
Chuck temperature (T)	400 °C
Deposition time (t)	4 minutes

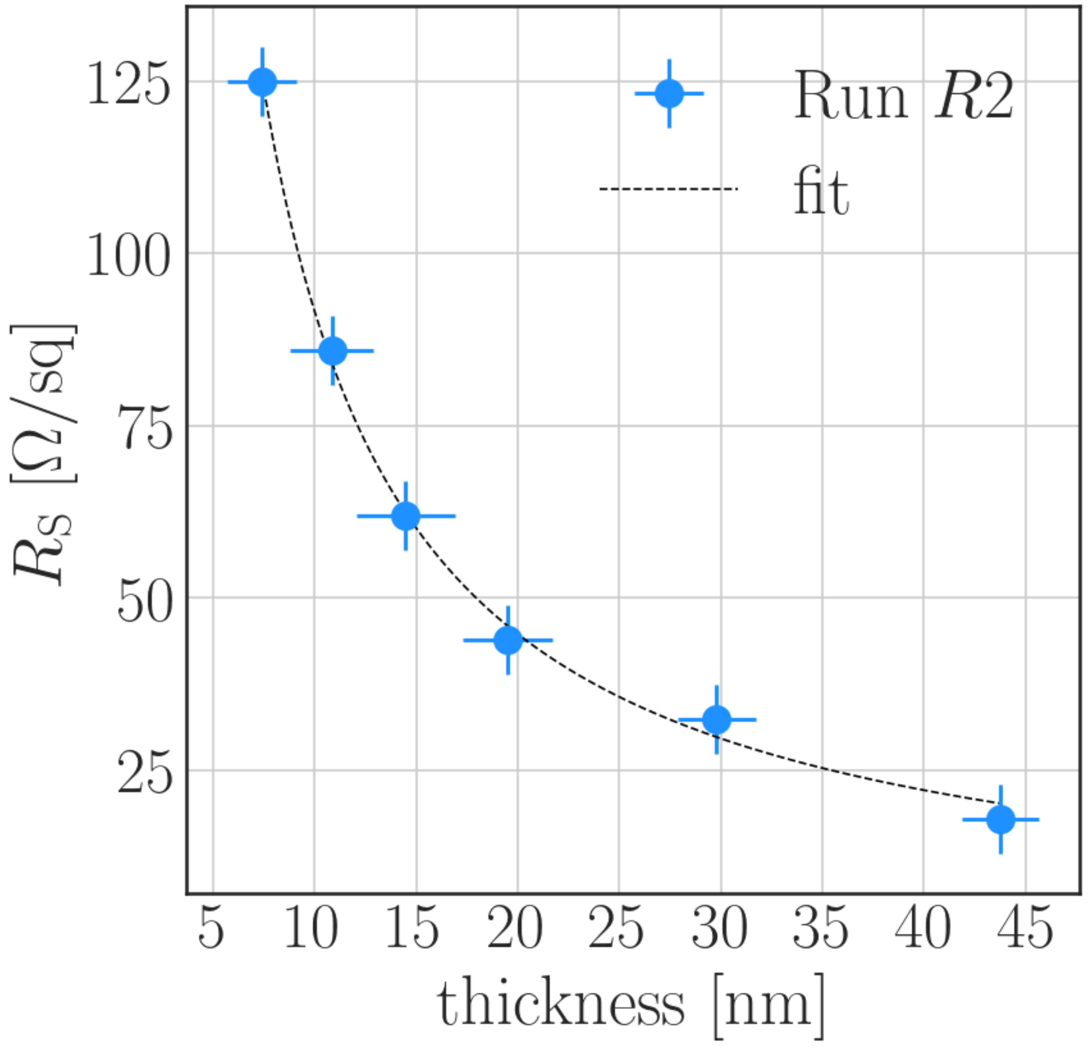
Varying time: $t \in [2, 9$ minute$]$

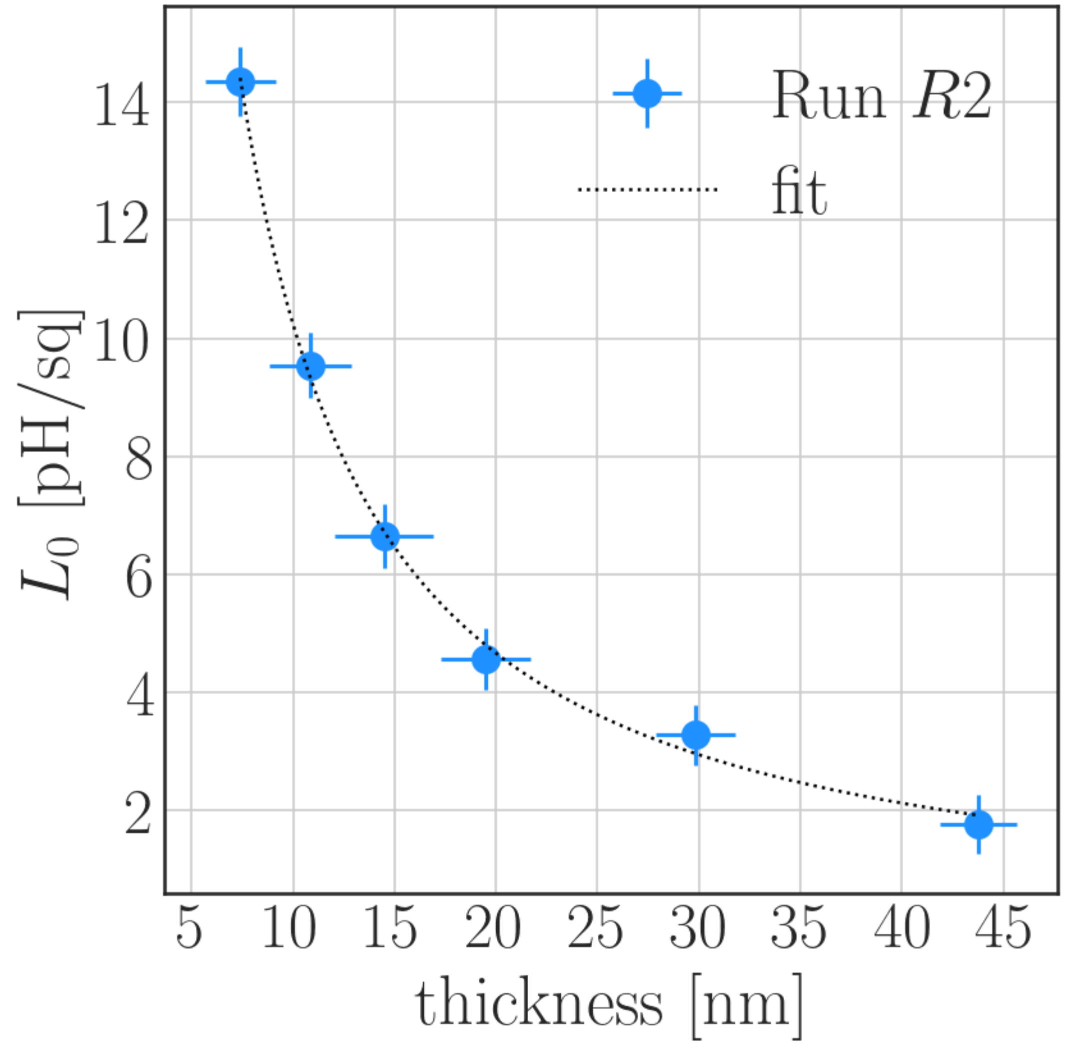
Fabrication run *R2*					
Wafer	t/minutes	T/nm	T_c/K	R_s/Ω/sq	L_0/pH/sq
W1	6.0	29.8	13.45	32.4	3.32
W2	2.0	7.4	12.03	125	14.7
W3	9.0	43.8	14.07	18	1.75
W4	4.0	19.5	13.35	44	4.70
W5	3.0	14.5	12.88	62	6.64
W6	2.5	10.8	12.45	86	9.53

$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$

3. Fine-tuning of the deposition recipe







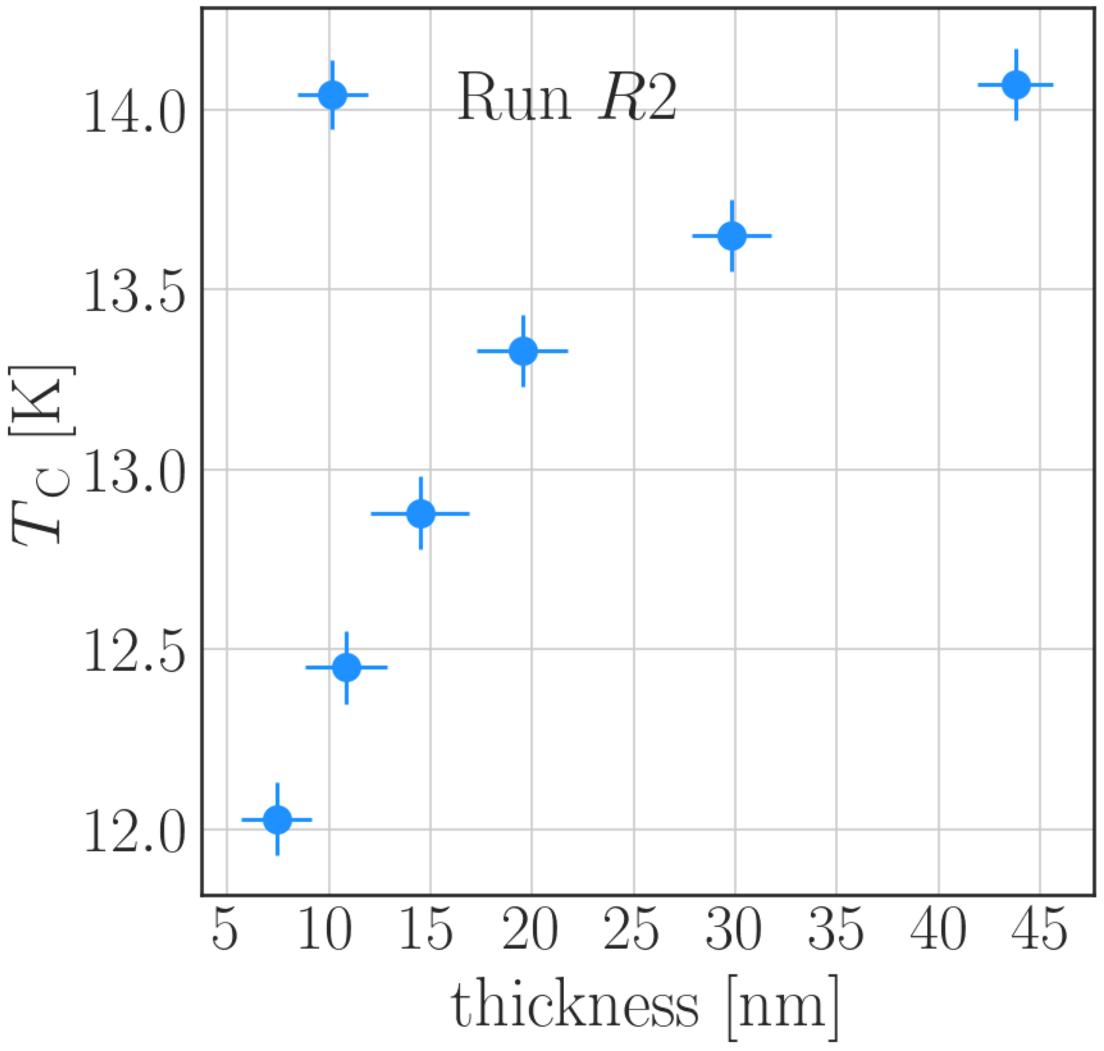
Fit: $R_S(h) = \frac{\rho_0}{h} \cdot \left(1 + \frac{3}{8} \cdot \frac{l_b}{h}\right)$

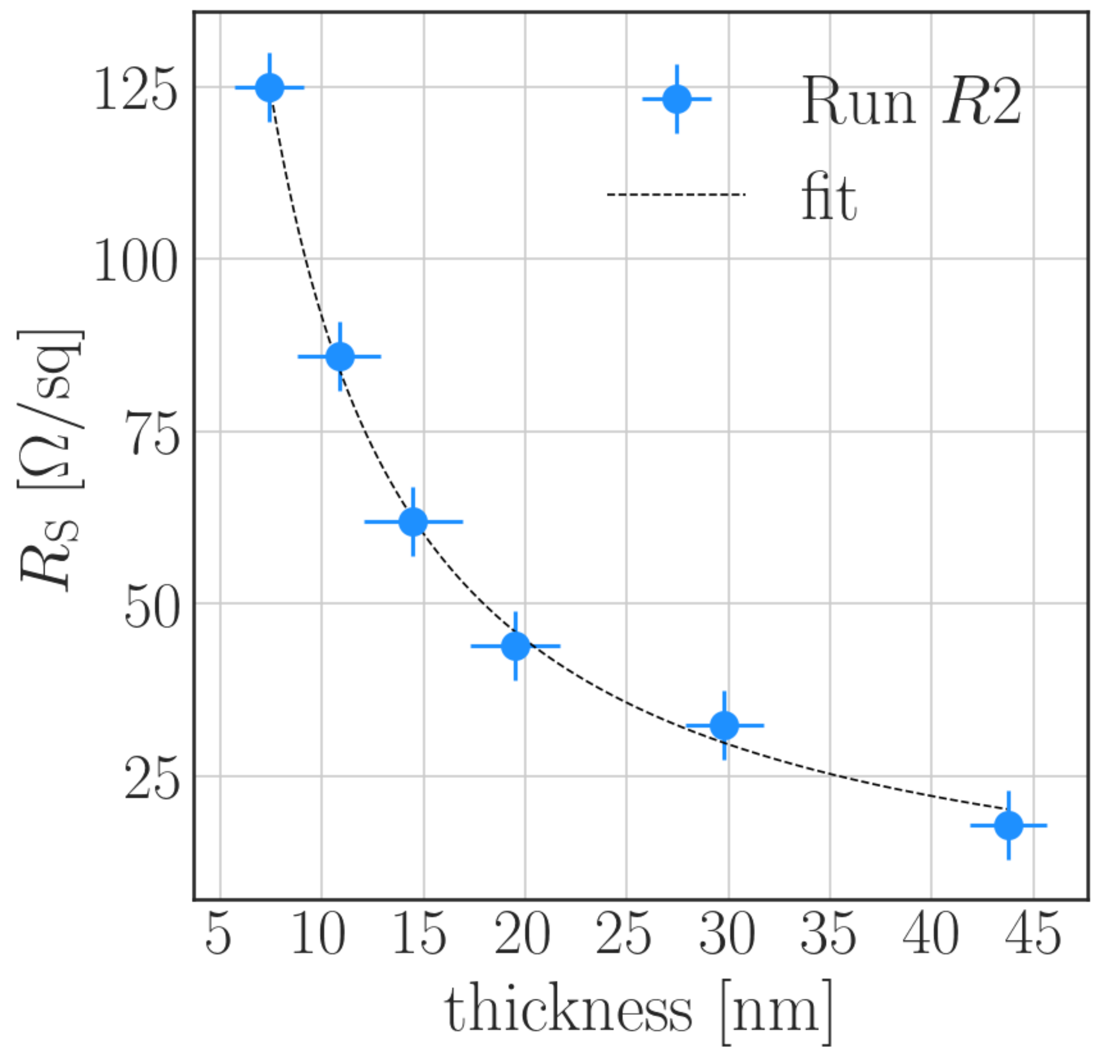
Fit: $L_0(h) = \frac{a}{h^\alpha}$

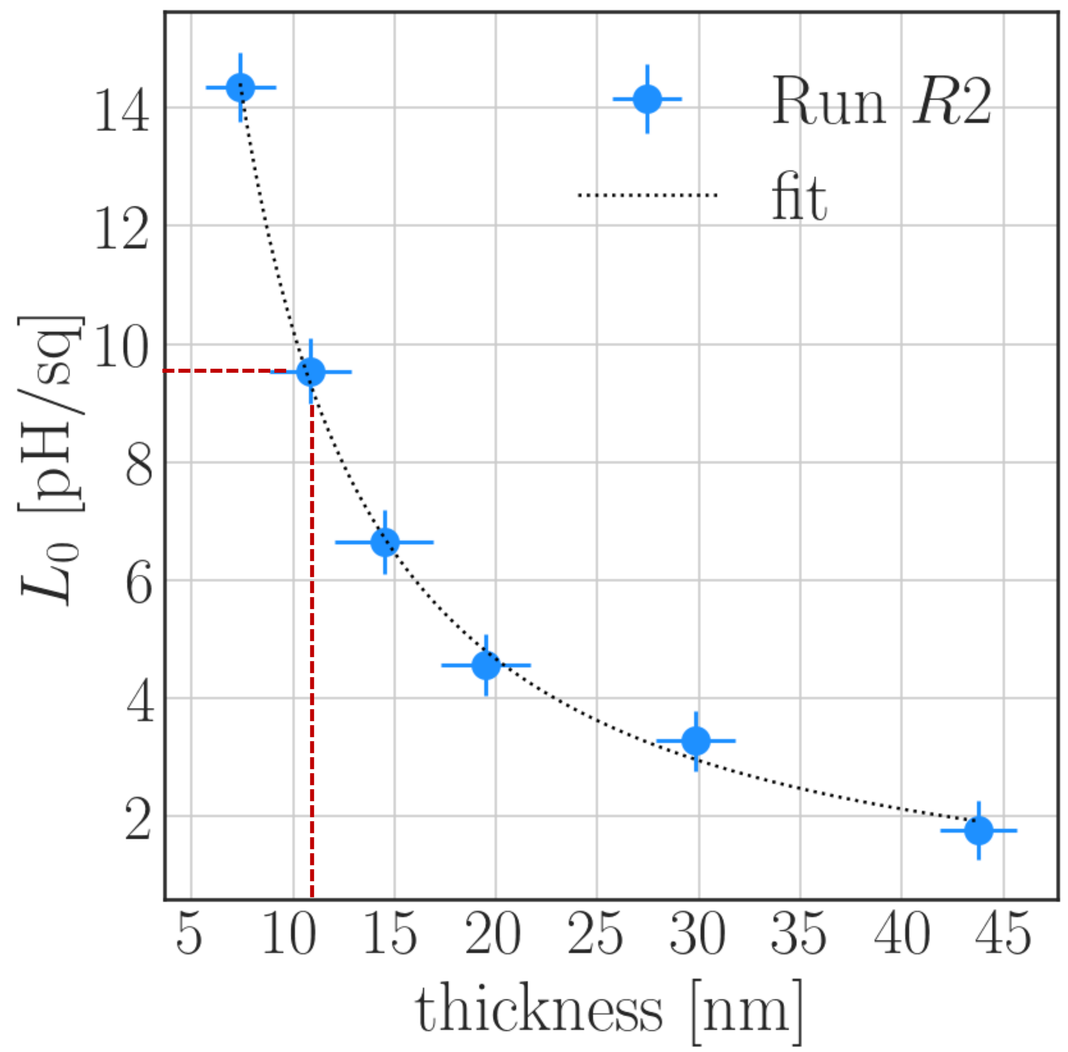
Fuch's model
(doi: 10.1017/S0305004100019952)

Phenomenological model

3. Fine-tuning of the deposition recipe







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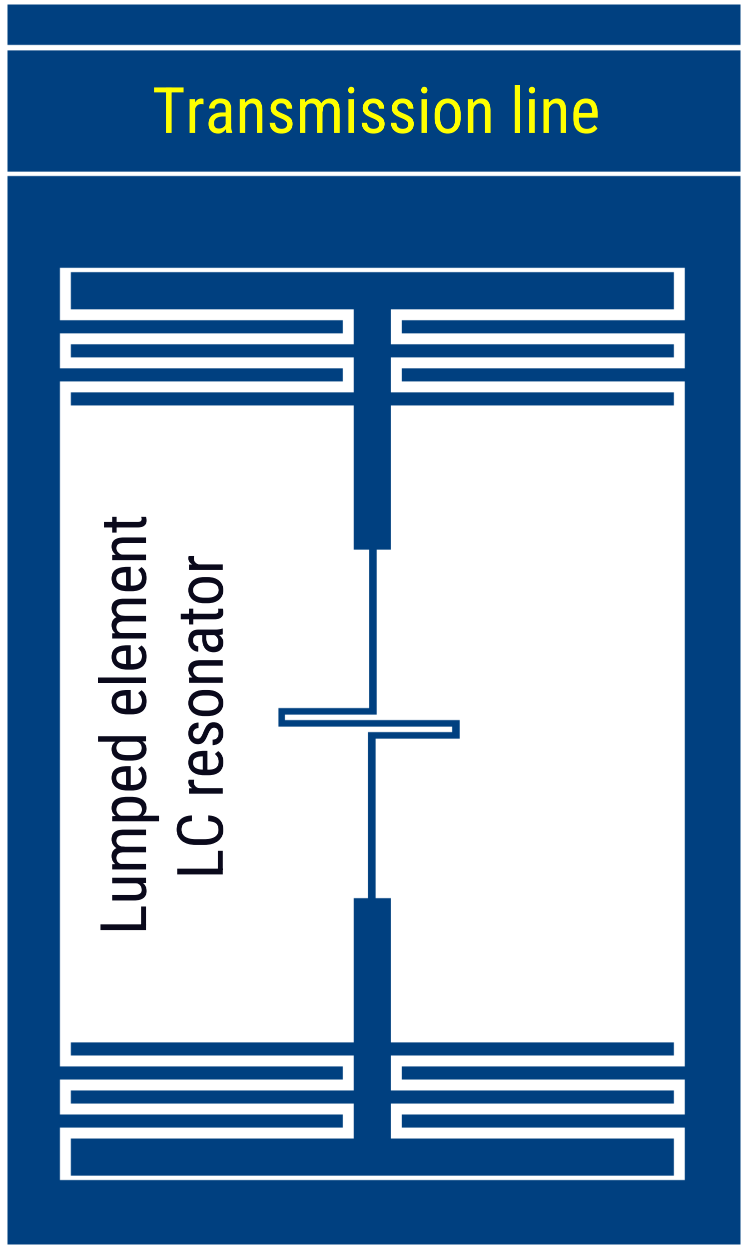
Fuch’s model
(doi: 10.1017/S0305004100019952)

Fit: $L_0(h) = \frac{a}{h^{\alpha}}$

Phenomenological model

4. Measurement of the kinetic inductance

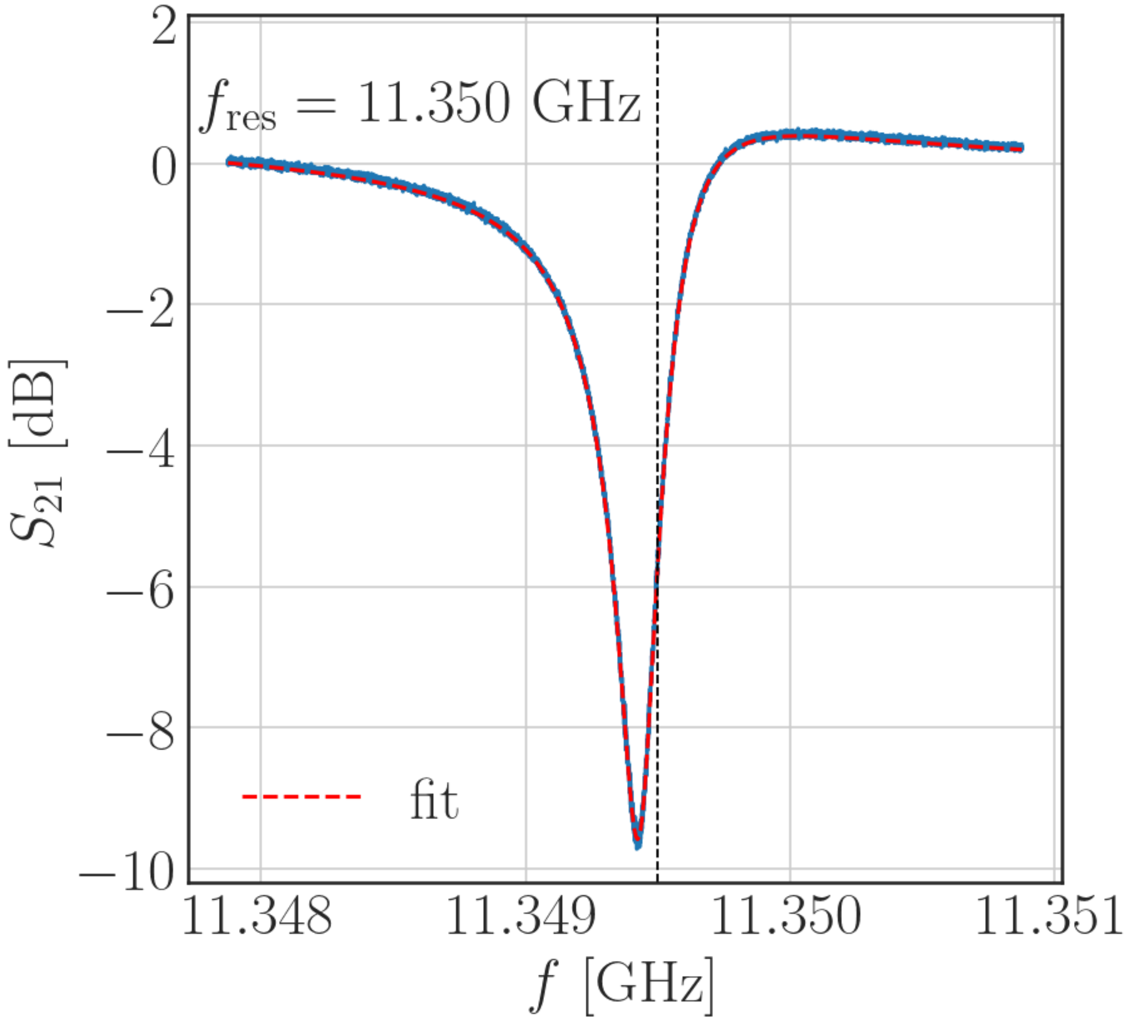
LC resonator: $f_{\text{res}} = \frac{1}{\sqrt{(L_g + L_0) \cdot C}}$



Metal
Substrate

doi: 10.1007/s10909-019-02251-1

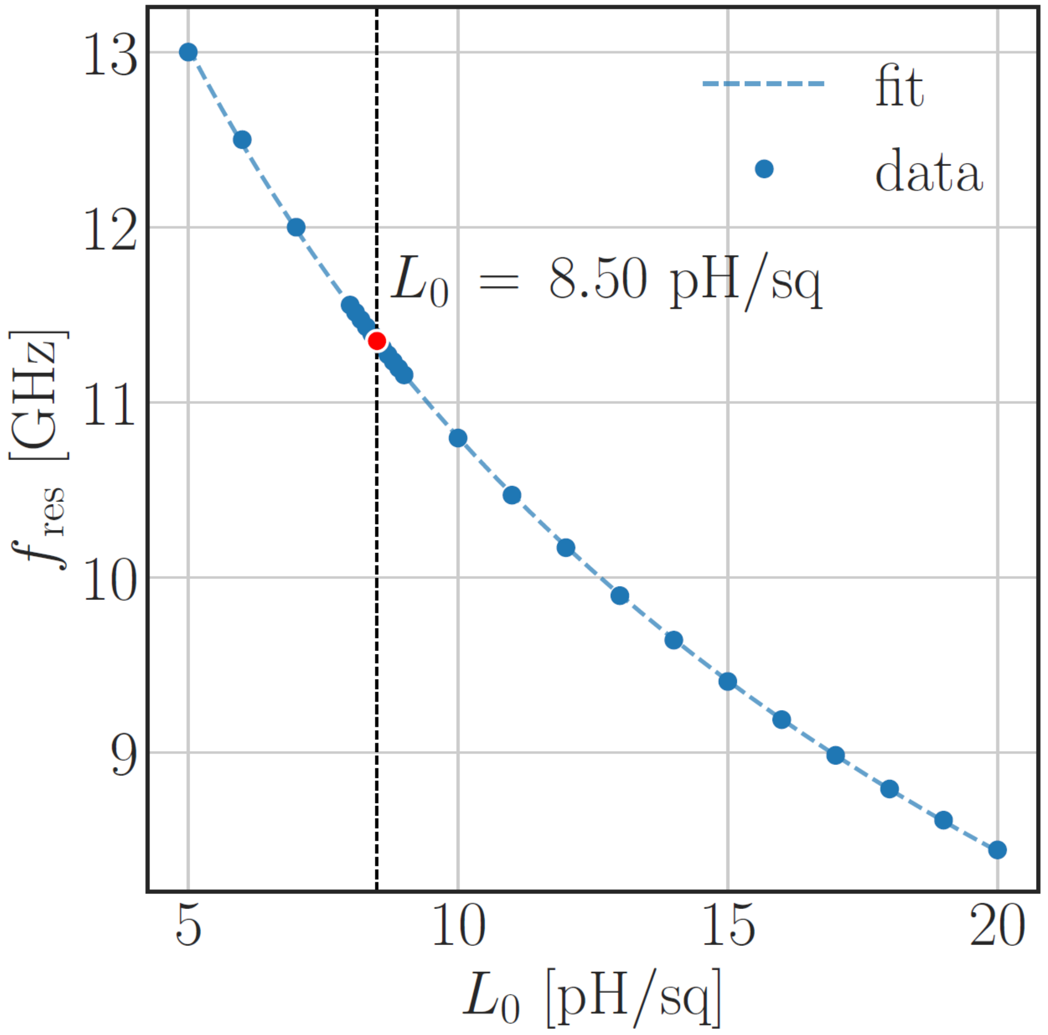
Measurement of f_{res}
at millikelvin



→ Discrepancy of ~10%
(within statistical/systematic uncertainties)

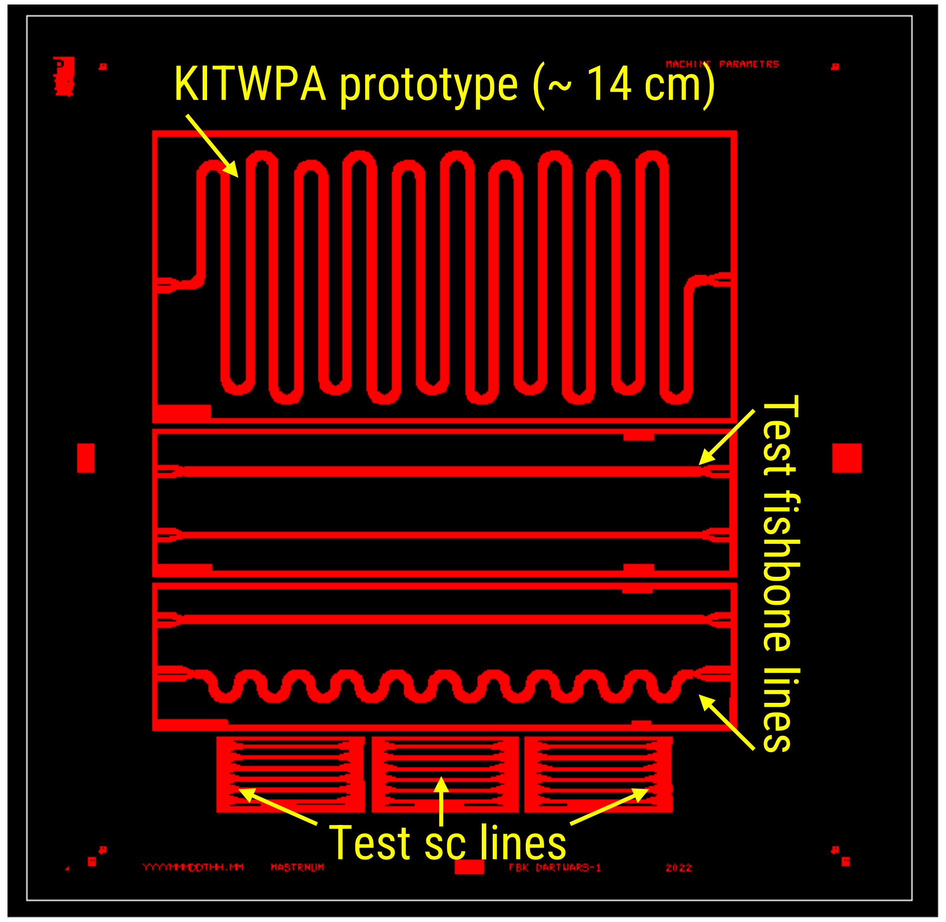
Simulations of the resonator
(fixing L_g and C, varying L_0)

→ "calibration curve":



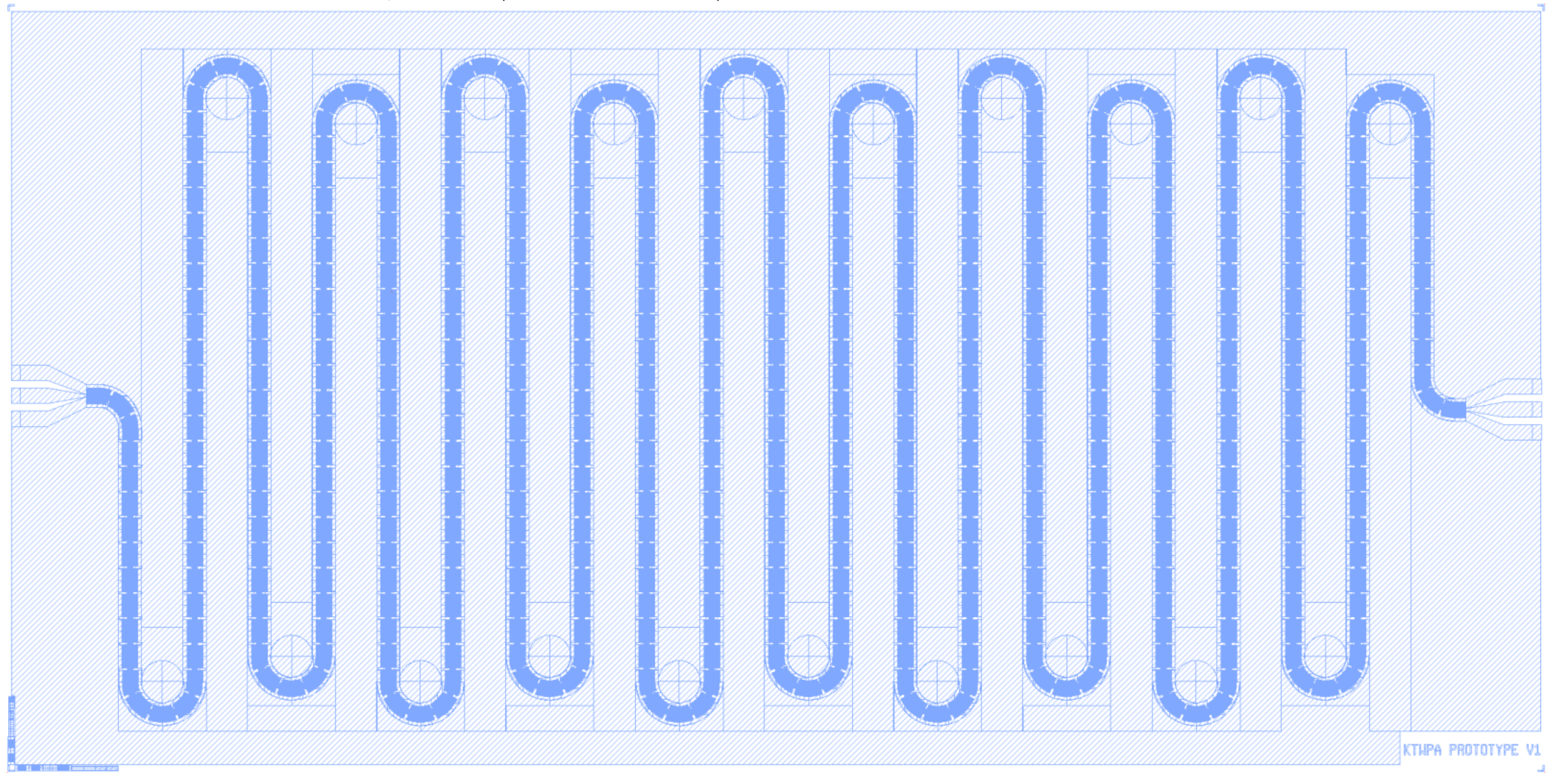
5. Fabrication of KI-TWPA prototypes: Designs

Stepper reticle DARTWARS-1:

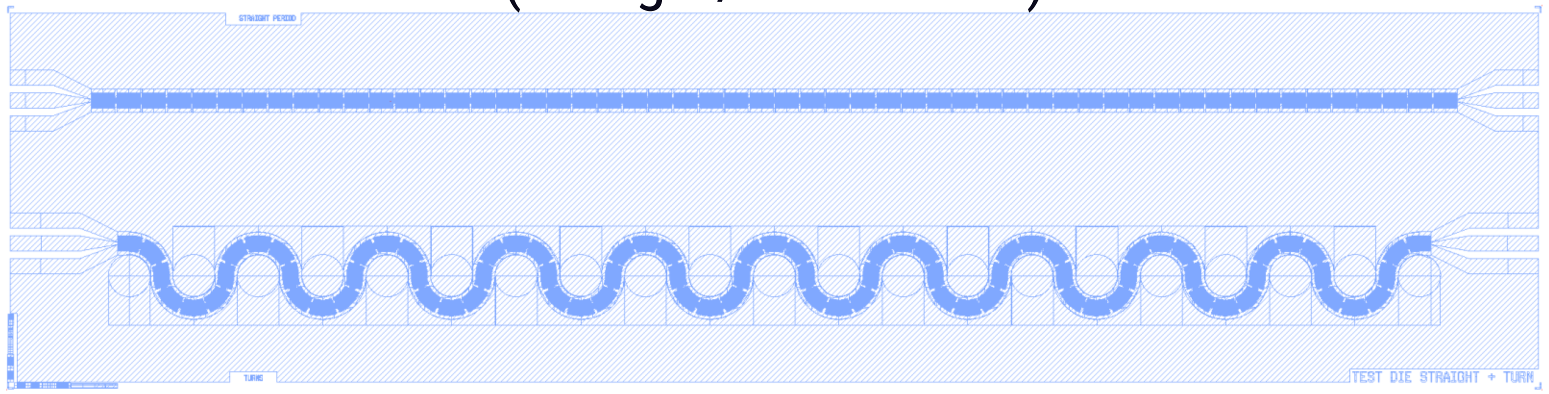


Note: reticle scale = 5:1

KITWPA prototype (~ 14 cm)



Test fishbone lines (straight/turn loaded)



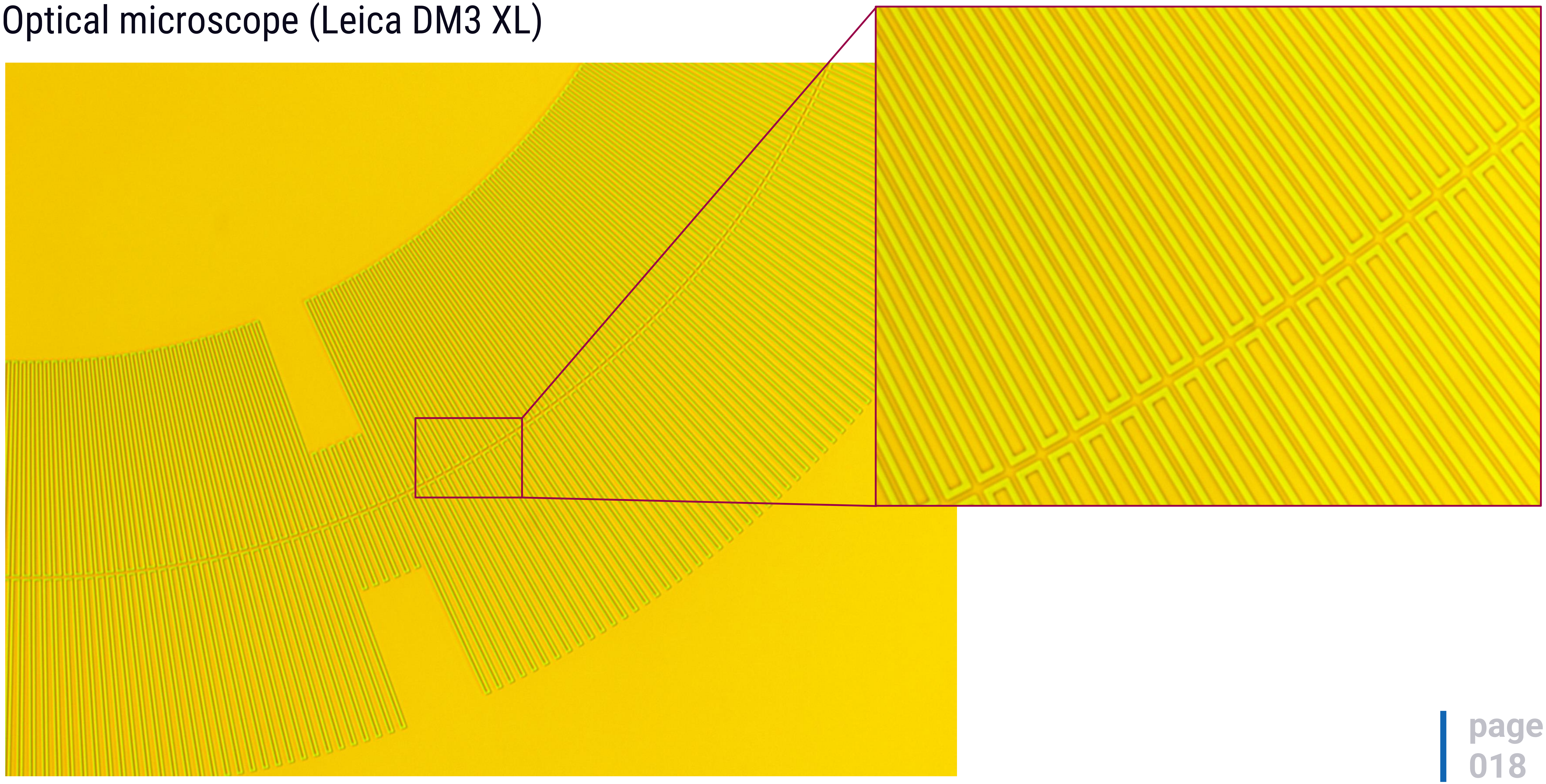
Test fishbone lines (straight unloaded)

5. Fabrication of KI-TWPA prototypes: Fab steps

#	Step	Description
1	Wafer labelling	*Labelling of the wafers*
2	Initial cleaning	*HF + IPA*
3	Oxidation	*Dry oxide, T = 975 °C, 90 min oxidation + 60 min annealing*
4	Control od oxide thickness	*Expected thickness: about 40 nm*
5	Initial wafer weighing	*Check weight with high precision balance*
6	Sputter deposition NbTiN	*rf-magnetron sputtering (Kenosistec), see recipe parameters*
7	Resistivity measurement	*Measure sheet resistance with 4 point probe*
8	Final wafer weighing	*Check weight with high precision balance*
9	Rinsing	*Remove developer traces from backside of the wafer*
10	Resist coating	*Resist coating, stepper resist*
11	Exposure	*Exposure with stepper (reticle DARTWARS-1)*
12	Developing	-
13	Optical inspection	-
14	Rinsing	-
15	Hard bake	*Hard bake, T = 120 °C, 1 h*
16	Oxygen plasma	*Oxygen plasma (T = 80 °C, 1 min) to adjust the structure size*
17	Dry etching	*Dry etching, SF6, 150 mT, 15 s + 15 s*
18	Remove resist	*Wet removal (acetone + IPA) OR ashing with oxygen plasma*
19	Final optical inspection	-
20	Coating of protective resist	-

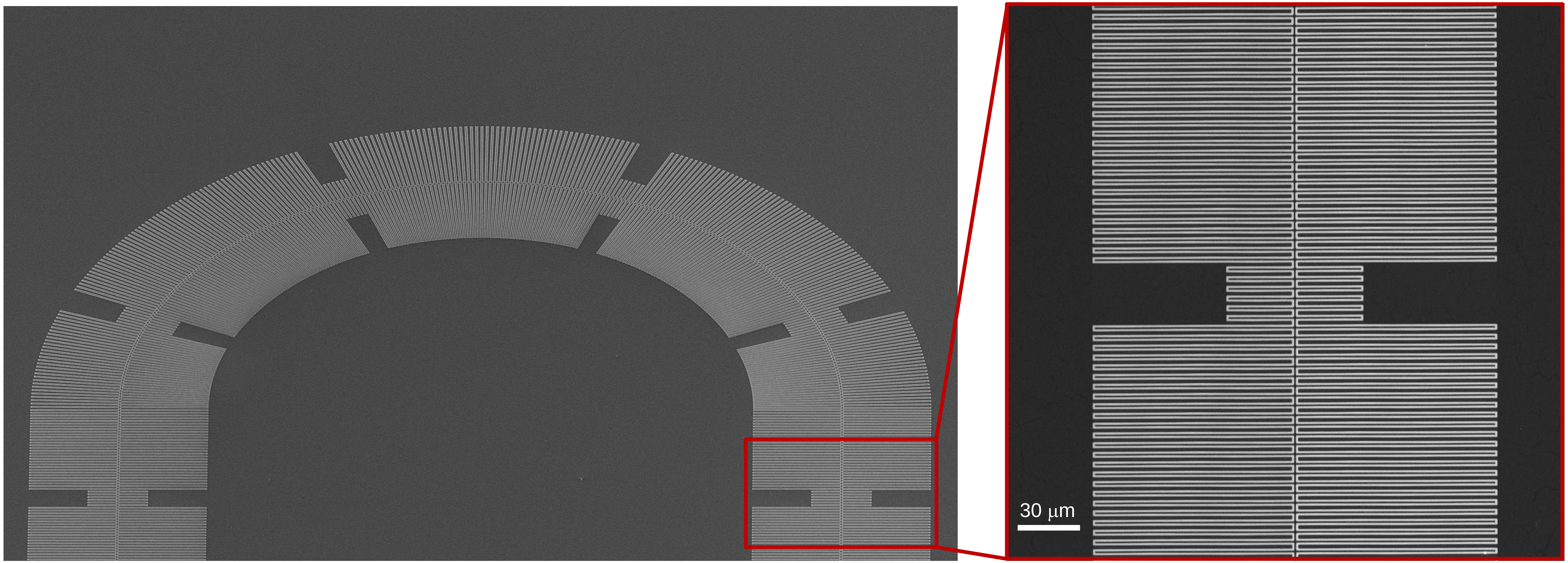
5. Fabrication of KI-TWPA prototypes: Photos

Optical microscope (Leica DM3 XL)



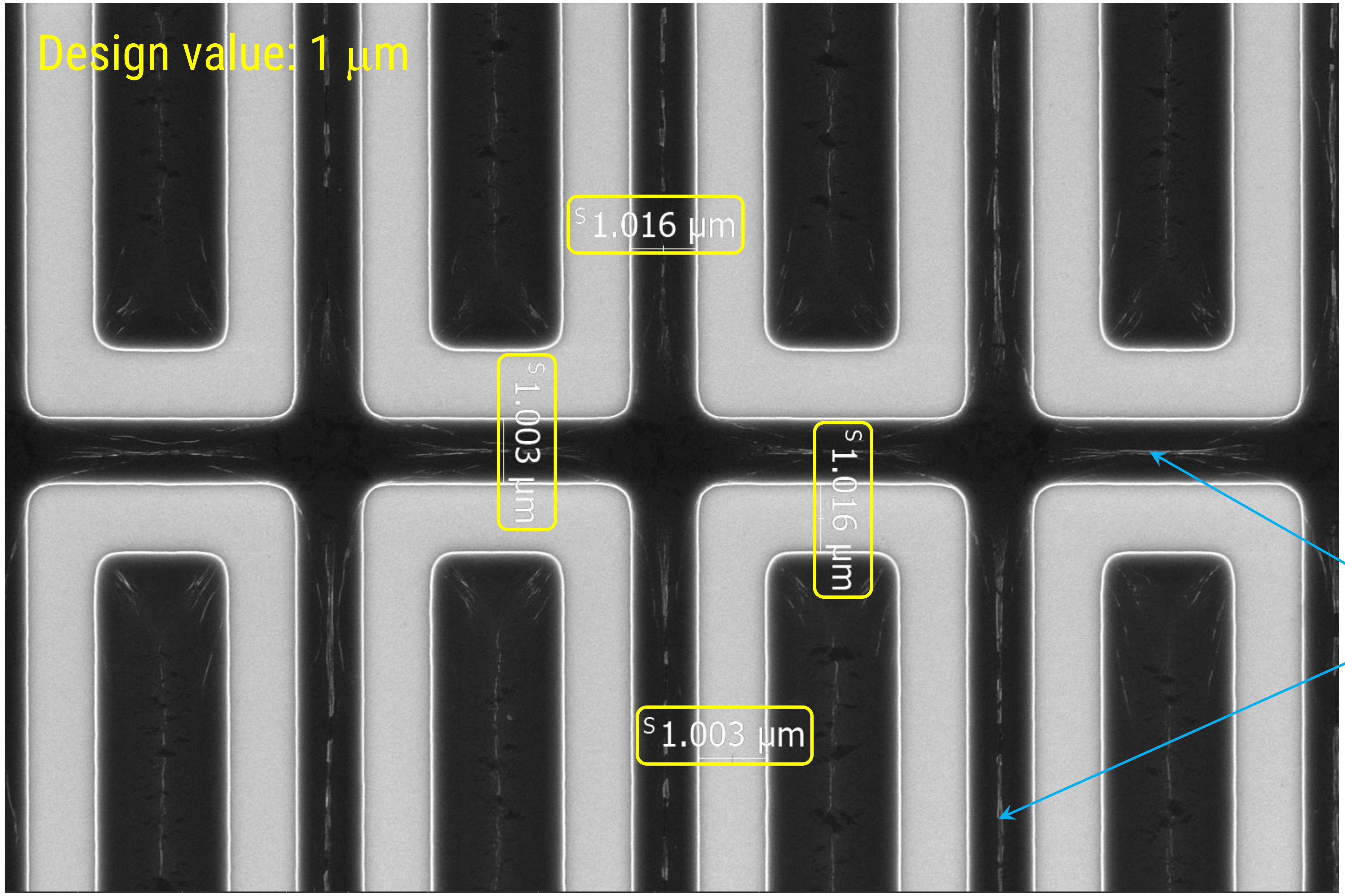
5. Fabrication of KI-TWPA prototypes: Photos

PFIB SEM Helios 5 CXe



5. Fabrication of KI-TWPA prototypes: Photos

PFIB SEM Helios 5 CXe



Size of structures (finger width / gap) matches the design value 🙂

Residuals of resist

→ for next productions: wet resist removal instead of ashing

Summary…

We have…

1. explored the sputtering parameters space
2. identified a promising deposition recipe and fine tuned it
3. verified experimentally the crucial parameters of the film:

4.

   $T_C \approx 12.5$ K, $R_S \approx 90\ \Omega$/sq and $L_0 \approx 8.5$ pH/sq

   → **match** with target values!
4. Fabricated the first KI-TWPA prototypes

Summary…

We have…

1. explored the sputtering parameters space
2. identified a promising deposition recipe and fine tuned it
3. verified experimentally the crucial parameters of the film:
   $T_C \approx 12.5$ K, $R_S \approx 90\ \Omega$/sq and $L_0 \approx 8.5$ pH/sq
   → **match** with target values!
4. Fabricated the first KI-TWPA prototypes

… & Outlook

We will…

1. fully characterize the KI-TWPA prototypes at millikelvin (I_*, signal loss)
2. if necessary, improve the film characteristics
3. proceed with the final designs and microfabrication

thank you.