MoRe as CNT growth-compatible superconductor[1, 2]

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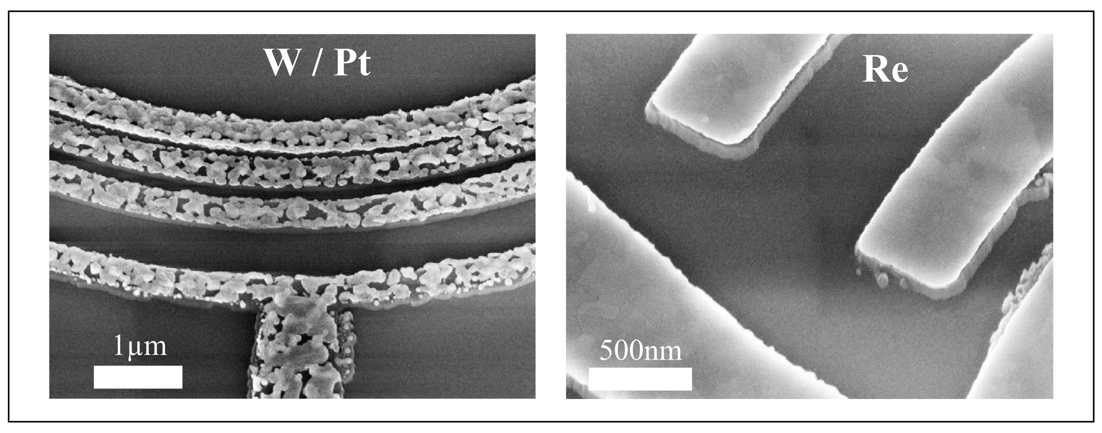
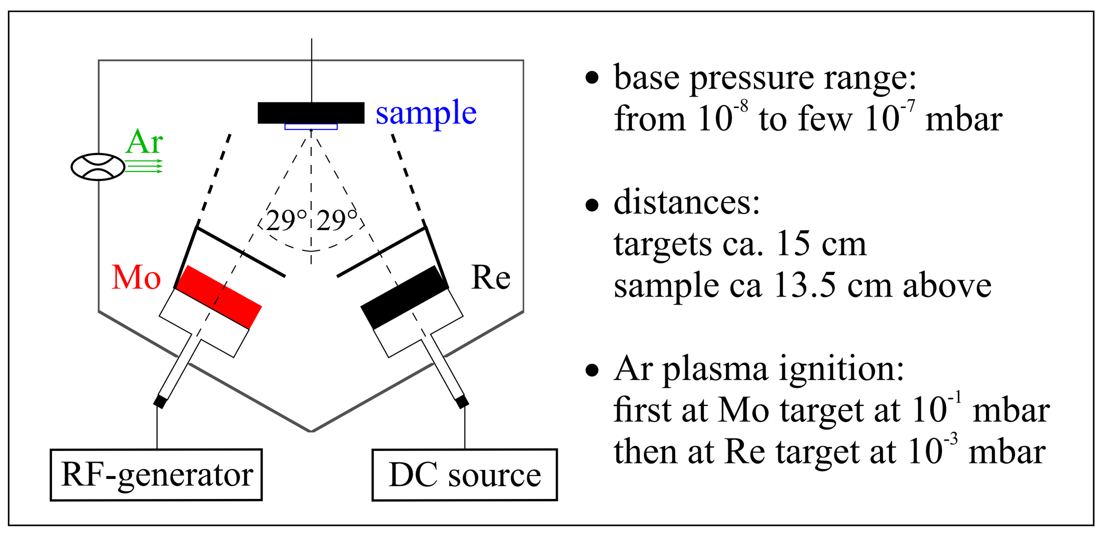
Motivation



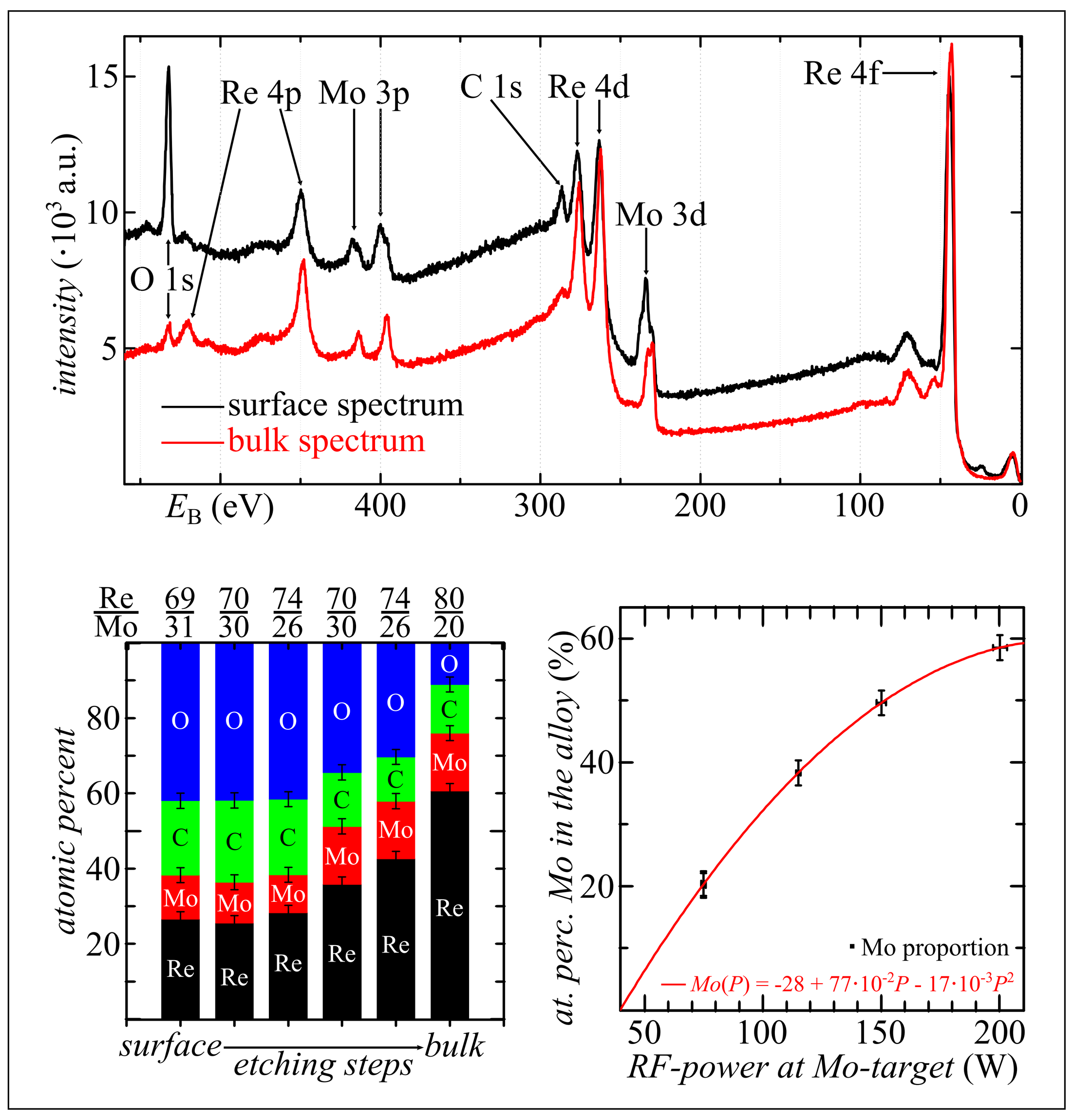
- ultra-clean carbon nanotubes: directly grown over prefabricated contact electrodes [3, 4, 5, 6]
- growth conditions: 850°C for 10-15 minutes in CH_4/H_2-atmosphere, plus heating / cooling
- MoRe alloys: high stability, superconducting critical temperatures up to $T_c = 15\,$K [6, 7, 8]

Co-sputtering

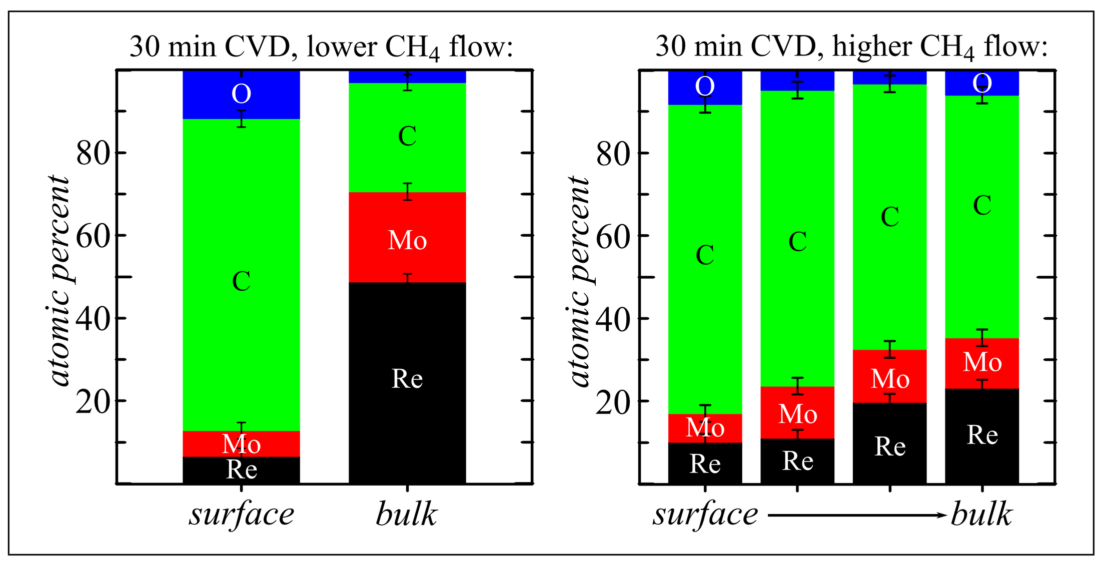


Resulting tunable alloys

- XPS, *in situ* Ar sputtering; use area sensitivity factors for Re 4f-, Mo 3d-, C 1s-, and O 1s-peaks
- observations for all films: molybdenum oxides on the surface, no rhenium oxides detectable
- Re enrichment in bulk, Mo at surface [9]

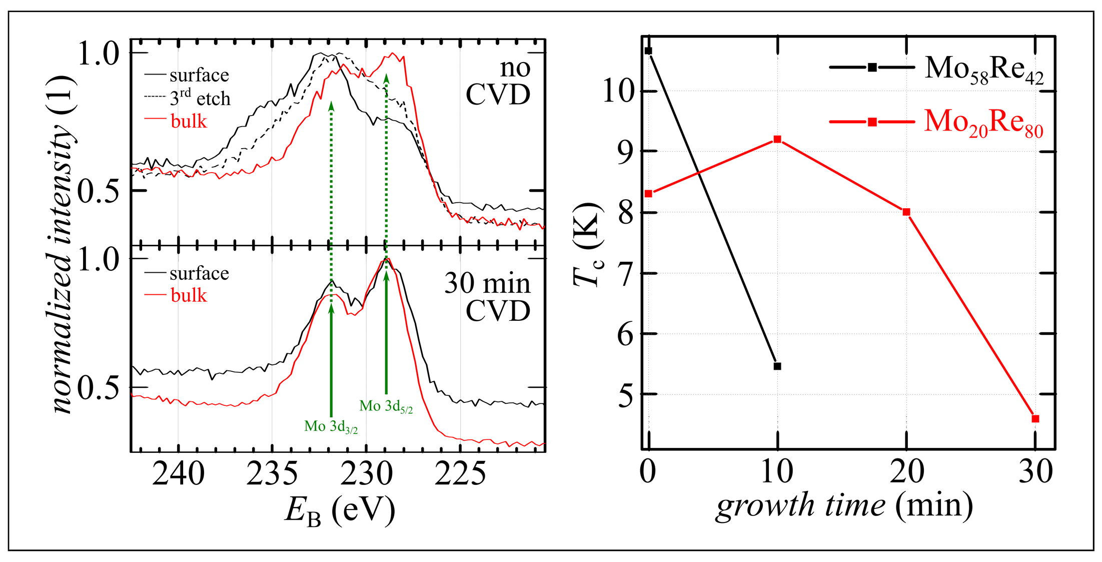


Influence of the CVD process



- diffusion of carbon into the alloy, enhanced with increasing CH_4 gas flow

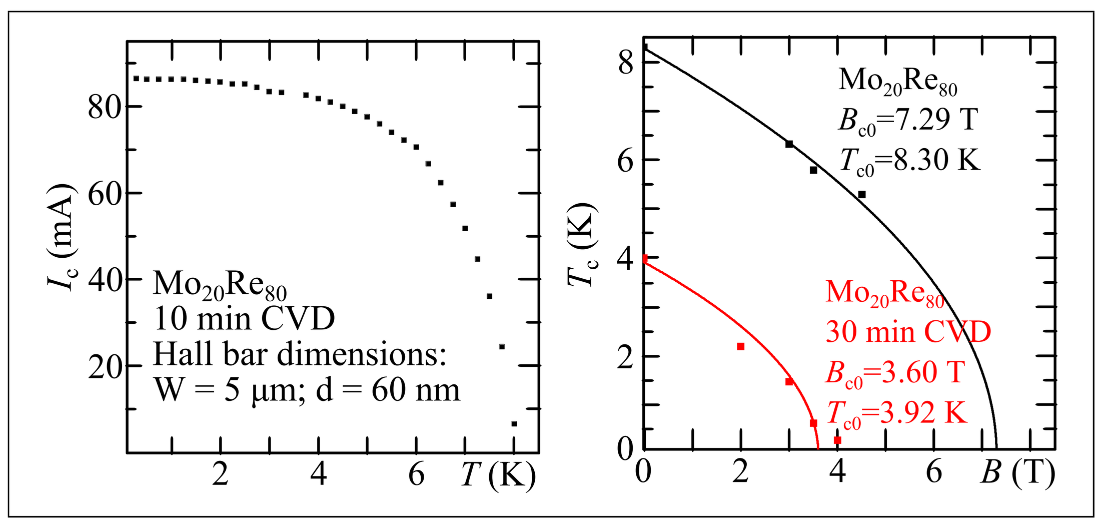
Influence of the CVD process



- reduction of molybdenum oxides to atomic Mo
- structural changes in the bulk, f.ex. from $Mo_{20}Re_{80}$ to $Mo_{31}Re_{69}$

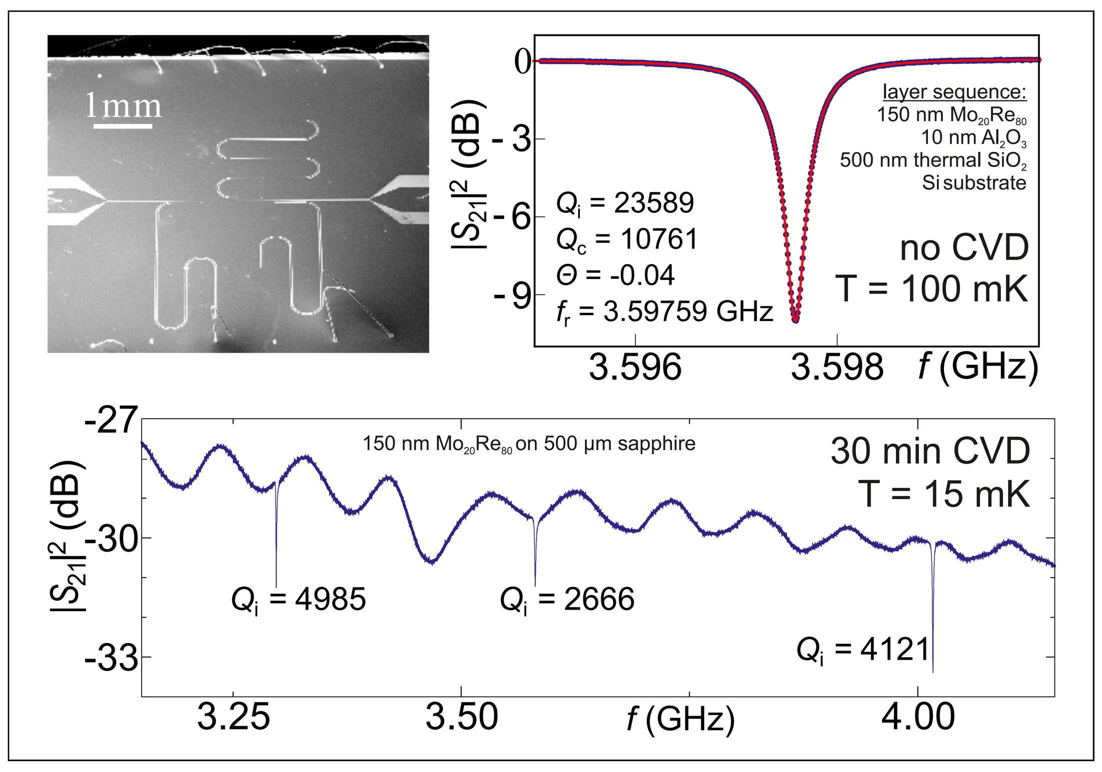
DC conductance properties

- both annealing and degradation due to CVD
- $Mo_{20}Re_{80}$ exhibits highest resilience in dc
- maximal critical current density $j_c = 2.7\cdot10^5\,\frac{A}{mm^2}$ observed after 10 minutes CVD



Coplanar resonators

- $\lambda/4$-resonators $\longrightarrow$ high frequency properties
- fit transmission resonances [11], extract Q_i, Q_c
- after CVD: $Q_i \leq 5000$ observed

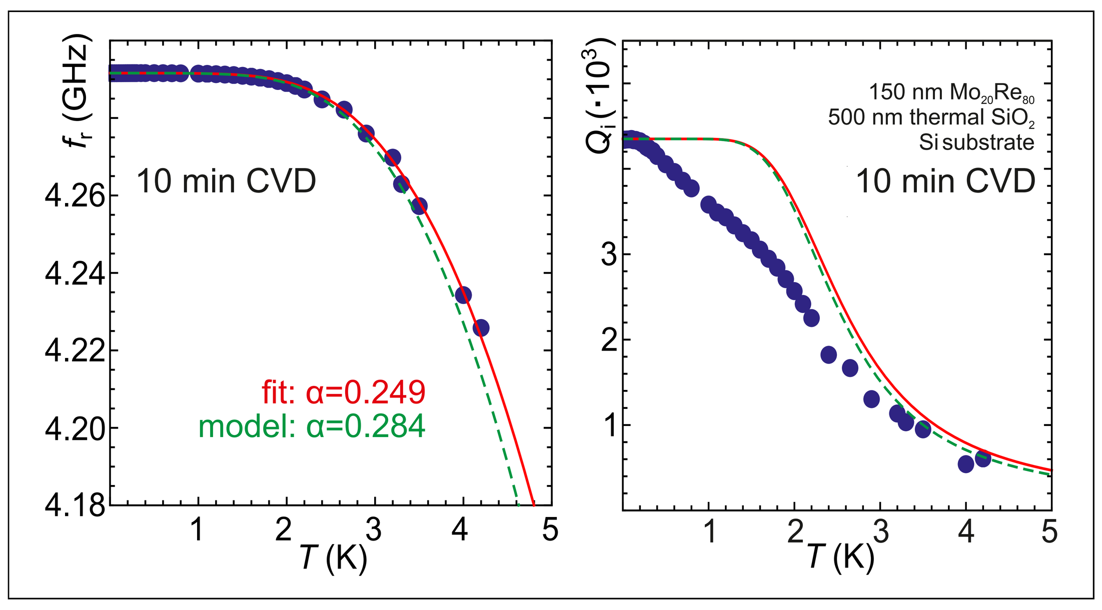


Temperature dependence (I)

- high temp.: Mattis-Bardeen theory [12, 13]

$$\frac{\delta f_r}{f_0} = \frac{\alpha_0}{2}\frac{\delta\sigma_2}{\sigma_2} \qquad \delta\left(\frac{1}{Q_i}\right) = \alpha_0\frac{\delta\sigma_1}{\sigma_2}$$

- kinetic inductance fraction $\alpha_0 = 0.22 \overset{CVD}{\longrightarrow} 0.26$
- internal quality factor $Q_i = 24000 \overset{CVD}{\longrightarrow} 4000$



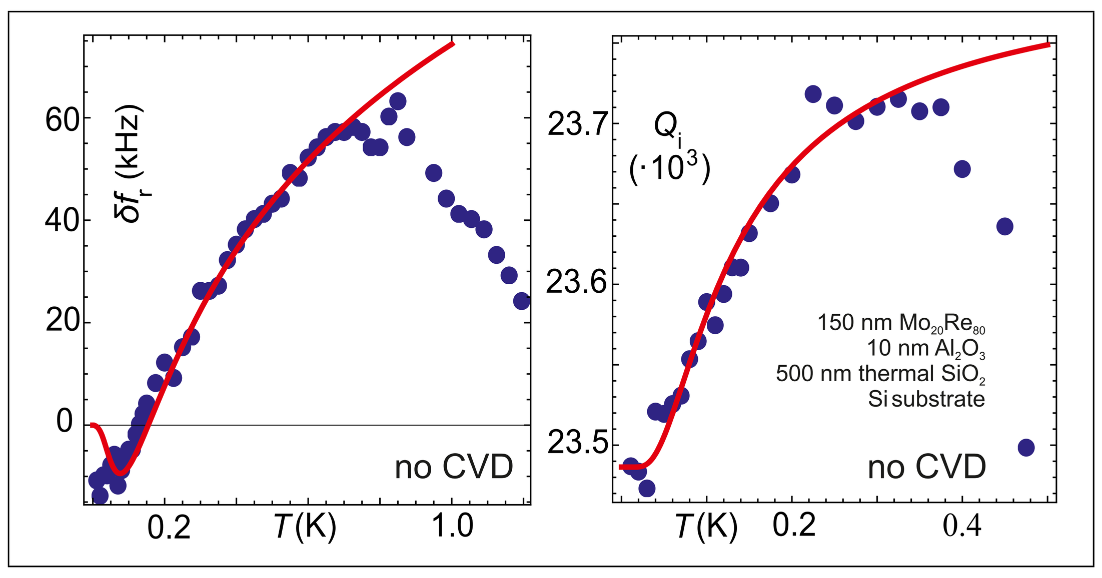
- $Q_i(T) \leftrightarrow$ finite quasiparticle lifetime [14]?

Temperature dependence (II)

- low temp.: two-level systems in substrate [11]

$$\frac{\delta f_r}{f_0} = \frac{F\vartheta}{\pi}\left[\mathrm{Re}\Psi\left(\frac{1}{2}+\frac{1}{2\pi i}\frac{hf_r(T)}{k_B(T)}\right) - \ln\left(\frac{1}{2\pi}\frac{hf_r(T)}{k_B(T)}\right)\right]$$

$$\frac{1}{Q_i} = F\vartheta_{eff}\tanh\left(\frac{hf_r(T)}{2k_BT}\right) + \frac{1}{Q_{other}}$$



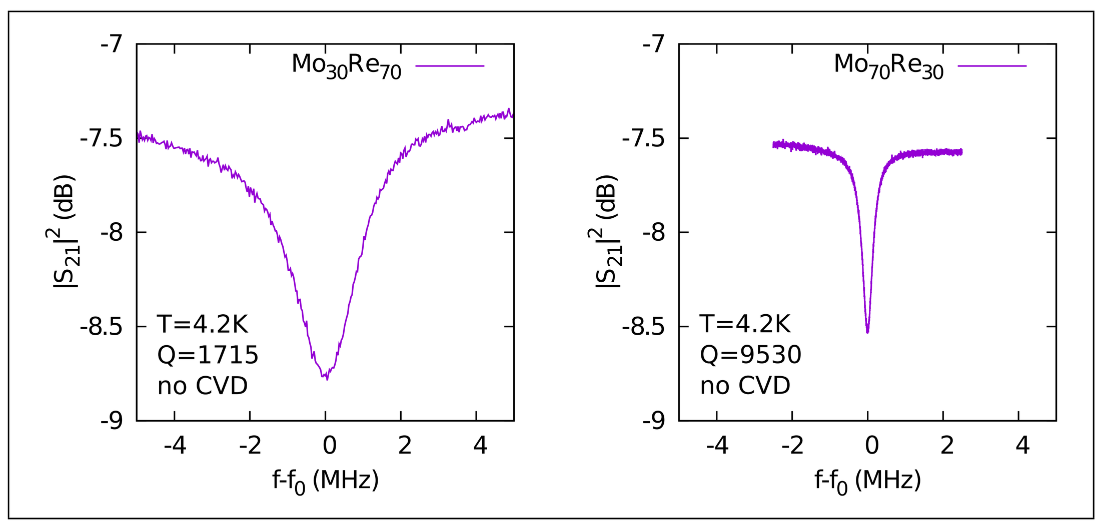
- from f: $F\vartheta \approx 4.0\cdot10^{-5}$ unchanged by CVD
- from Q_i: $F\vartheta_{eff} = 5.7\cdot10^{-7} \overset{CVD}{\longrightarrow} 1.6\cdot10^{-6}$ (ϑ_{eff} accounts for partial TLS saturation)
- after CVD, Q_{other} dominates fit ($\longrightarrow$?)

Prefabricted alloy targets

- use prefabricated alloy sputter targets instead of co-sputtering
- tests with nominal $Mo_{30}Re_{70}$ and $Mo_{70}Re_{30}$
- No large differences in dc properties

	$Mo_{30}Re_{70}$ no CVD	$Mo_{30}Re_{70}$ 15min CVD	$Mo_{70}Re_{30}$ no CVD	$Mo_{70}Re_{30}$ 15min CVD
T_c (K)	7.8	8.1	7.6	7.4
j_c (10^3 A/mm^2)	25	26	26	21
ρ_{RT} ($10^{-7}\Omega$m)	5.6	6.9	4.6	**2.6**
$\rho_{\sim10K}$ ($10^{-7}\Omega$m)		6.7	4.4	**1.9**

$Mo_{30}Re_{70}$ vs. $Mo_{70}Re_{30}$



- resonator characterization at $T = 4\,$K: tentatively, larger values of Q_i for $Mo_{70}Re_{30}$

#	$Mo_{30}Re_{70}$, no CVD f (GHz)	Q_i	#	$Mo_{70}Re_{30}$, no CVD f (GHz)	Q_i
1	3.39	1715	1	3.08	9530
2	3.66	1600	2	3.35	11010
3	4.13	1480	3	3.48	830 (?)

- consistent with literature [6]
- however, large scatter between devices

References

[1] K. Götz *et al.*, Nanotech. **27**, 135202 (2016).
[2] S. Blien *et al.*, phys. stat. sol. (b) **253**, 2385 (2016).
[3] J. Kong *et al.*, Nature **395**, 878 (1998).
[4] J. Cao *et al.*, Nature Materials **4**, 745 (2005).
[5] A. Dirnaichner *et al.*, PRL **117**, 166804 (2016).
[6] V. Singh *et al.*, Appl. Phys. Lett., **105**, 222601 (2014).
[7] L. Testardi *et al.*, Sol. St. Com. **9**, 1829 (1971).
[8] J. Talvacchio *et al.*, J. L. Temp. Phys. **64**, 395 (1986).
[9] V. Seleznev *et al.*, SC. Sci. Tech., **21**, 115006 (2008).
[10] M. Aziz *et al.*, Appl. Phys. Lett., **104**, 233102 (2014).
[11] D. Pappas *et al.*, IEEE Trans. Appl. Superc., **21**, 871 (2011).
[12] D. Mattis *et al.*, Phys. Rev., **111**, 412 (1958).
[13] J. Gao *et al.*, J. L. Temp. Phys., **151**, 557 (2008).
[14] M. Žemlička *et al.*, Phys. Rev. B **92**, 224506 (2015).

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