# Micro Calorimeters - Production Technologies and Technological Challenges

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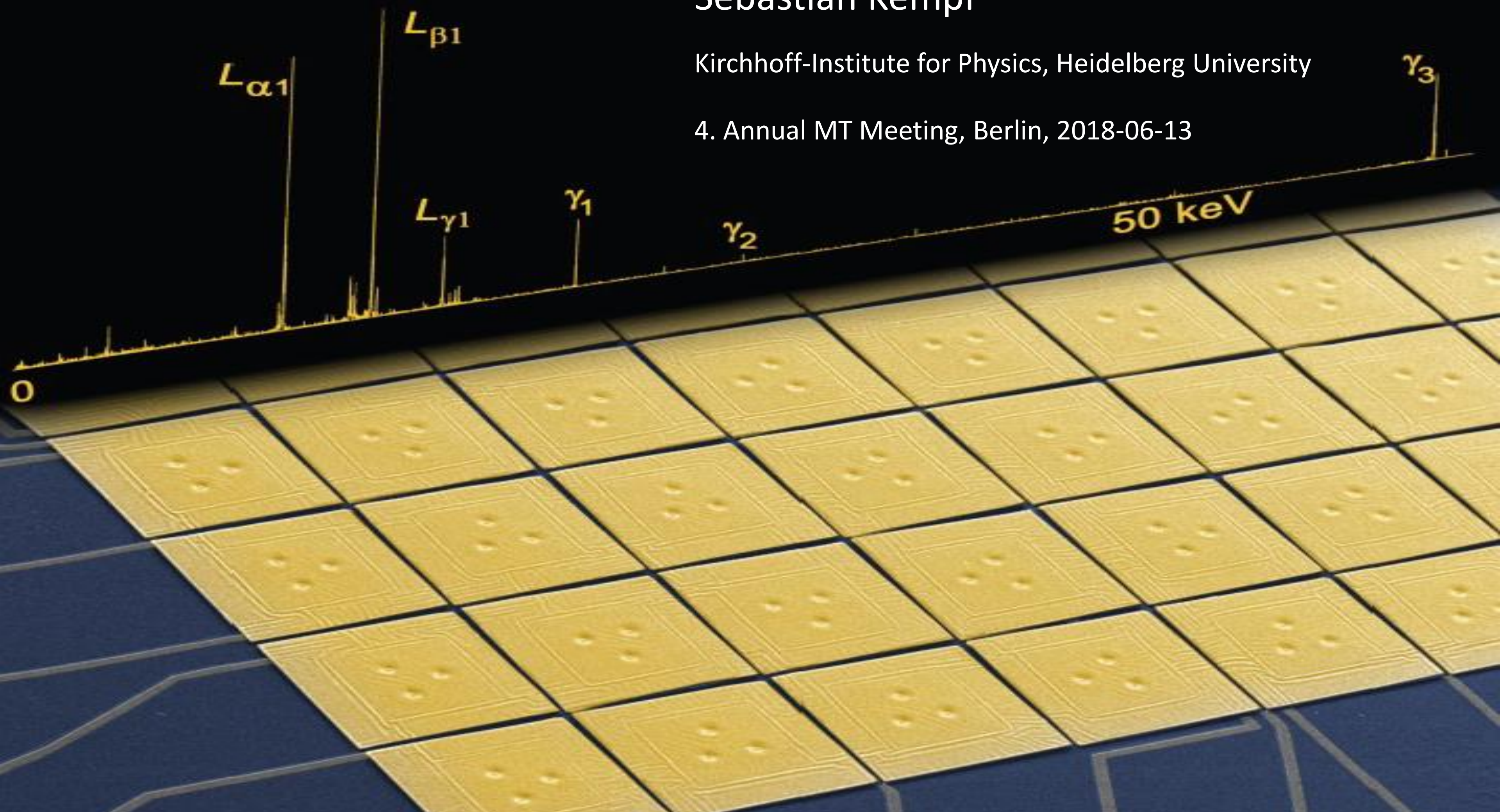
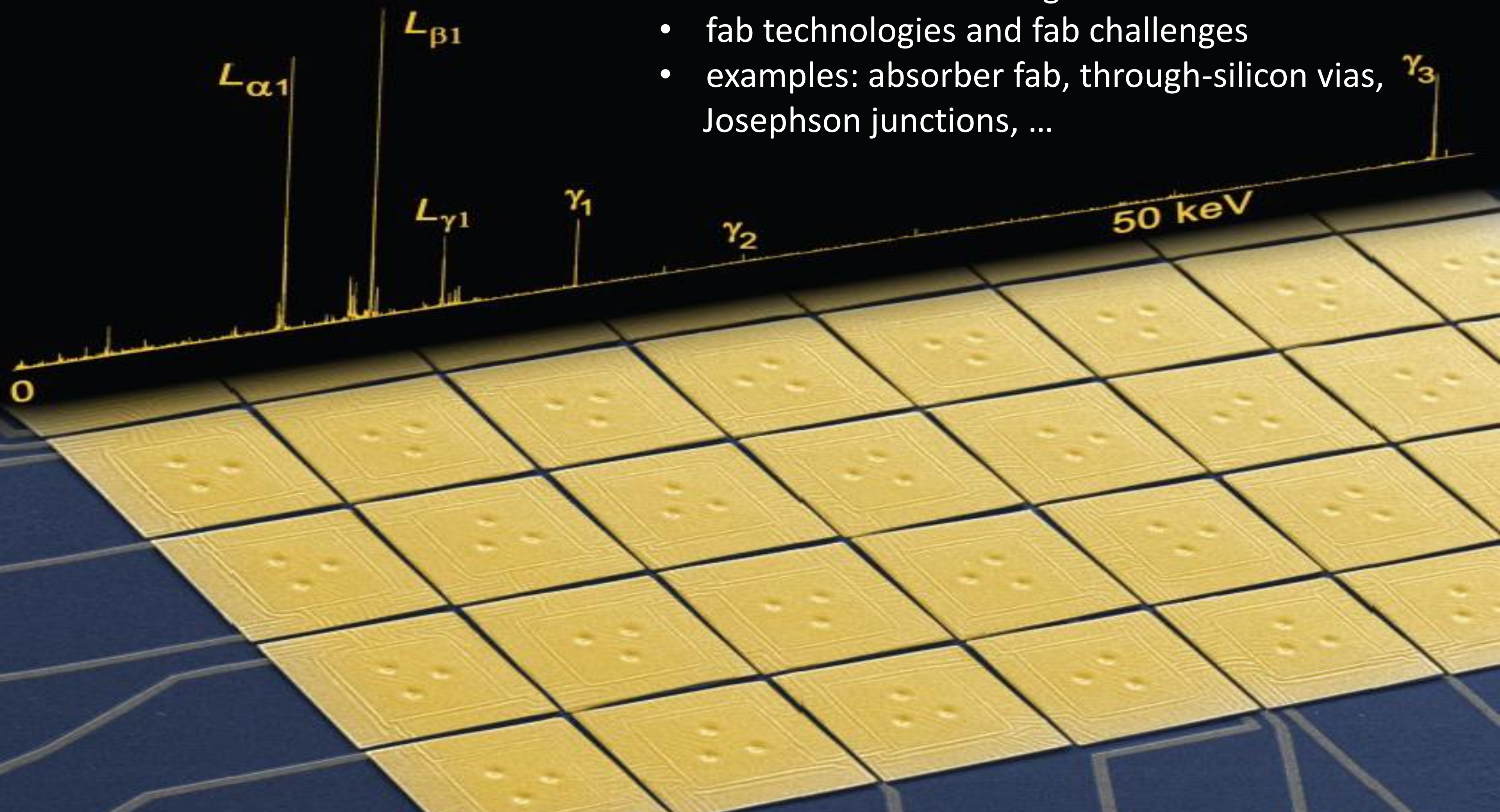
4. Annual MT Meeting, Berlin, 2018-06-13

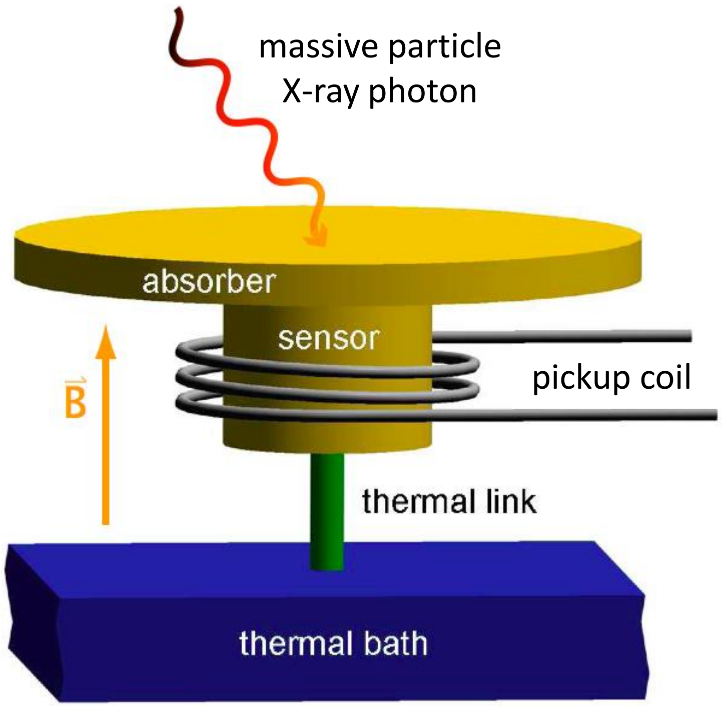


# Micro Calorimeters - Production Technologies and Technological Challenges

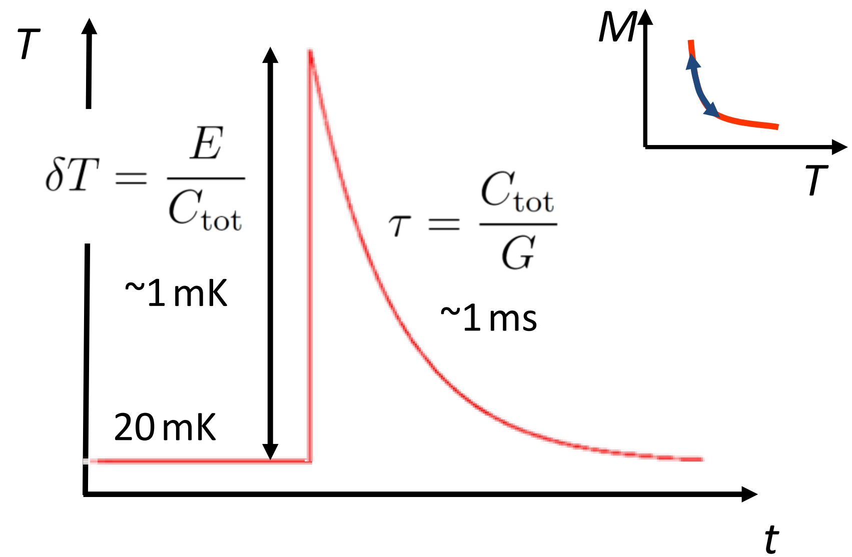
- reminder: metallic magnetic calorimeters
- fab technologies and fab challenges
- examples: absorber fab, through-silicon vias, Josephson junctions, …



# metallic magnetic calorimeter (MMC)



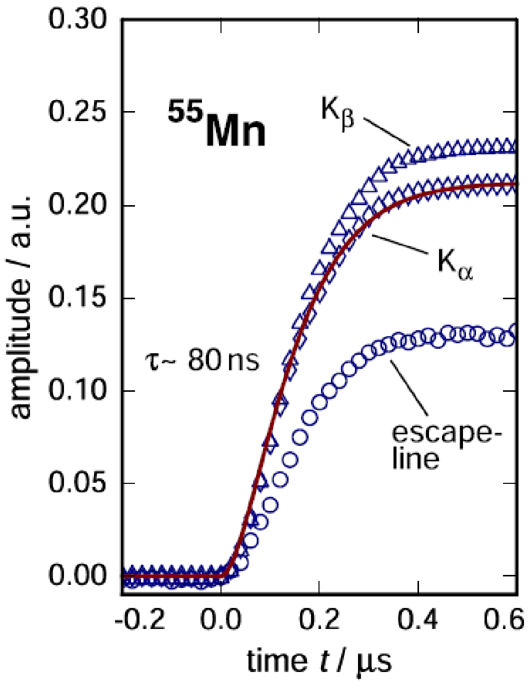

single detector event

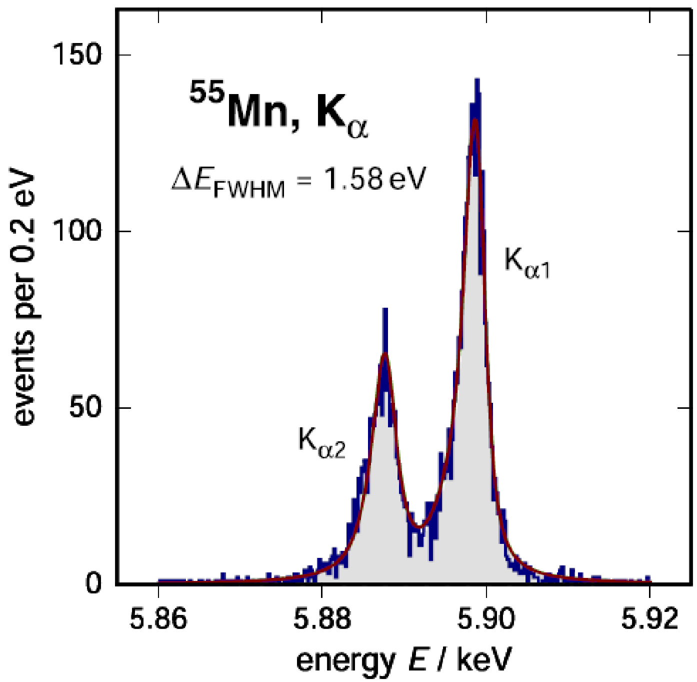


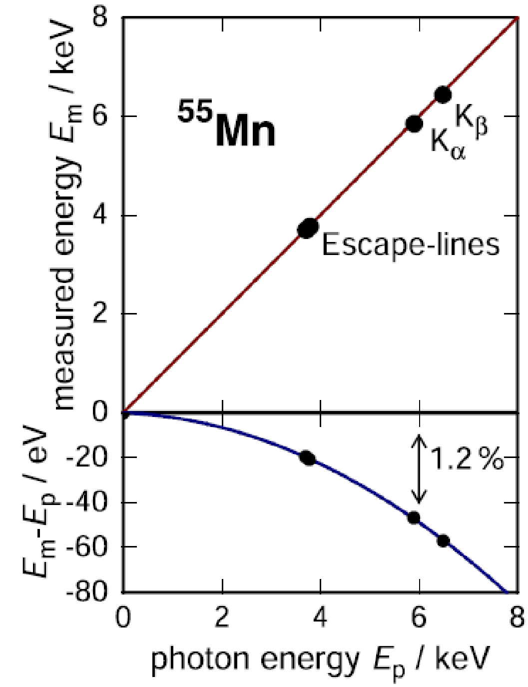

fundamental limit on energy resolution: $\Delta E_{\mathrm{FWHM}} \simeq 2{,}36\sqrt{4k_{\mathrm{B}}C_{\mathrm{Abs}}T^2}\sqrt{2}\left(\frac{\tau_0}{\tau_1}\right)^{1/4}$

# key features of metallic magnetic calorimeters

example: detector for soft X-ray spectroscopy




signal rise time
80 ns

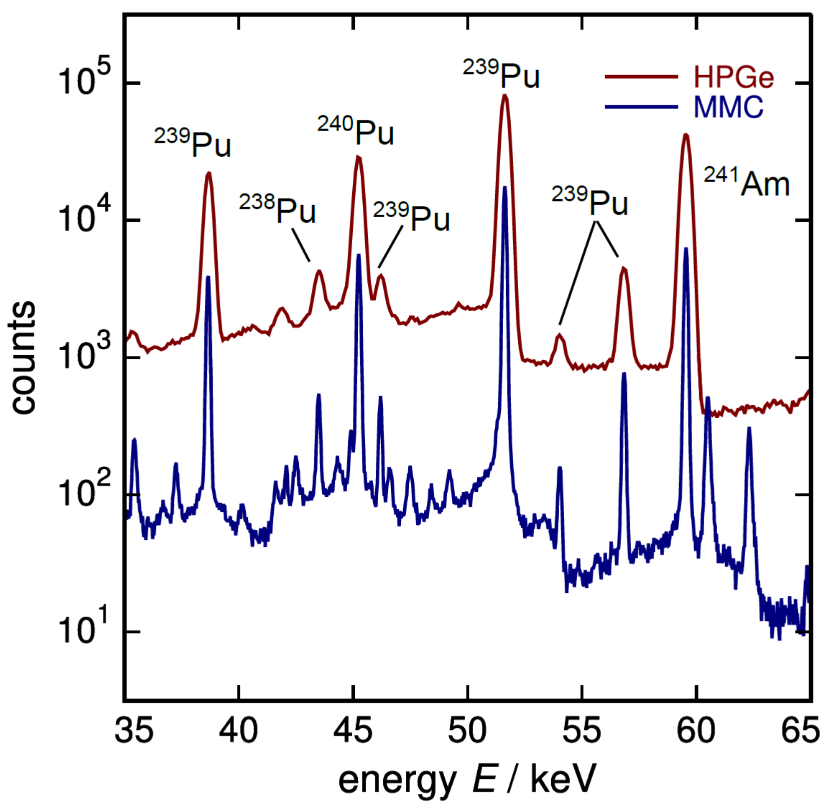
$\Delta E_{\mathrm{FWHM}}$ @ 6keV
1.6eV

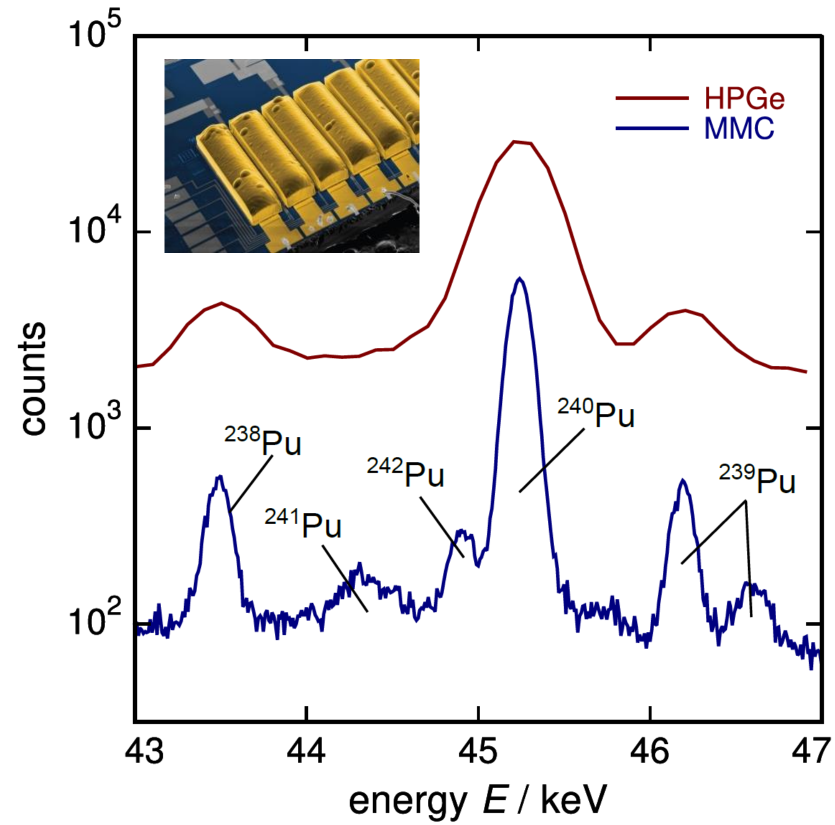
non-linearity @ 6keV
1.2%

outstanding interplay between highly sensitive magnetic thermometer and near quantum-limited amplifier

# nuclear safeguards with metallic magnetic calorimeters

γ-spectroscopy of a mixed Pu sample using MMCs




Pu isotope ratios same as determined with mass spectrometry

C. Bates *et al.*, J. Low Temp. Phys. **184** (2016) 351

# MMC all around the world


**atomic / molecular physics**
- X-ray spectroscopy
- highly-charged ions
- molecular ion chemistry
- Lamb-Shift measurements
- X-ray polarimetry

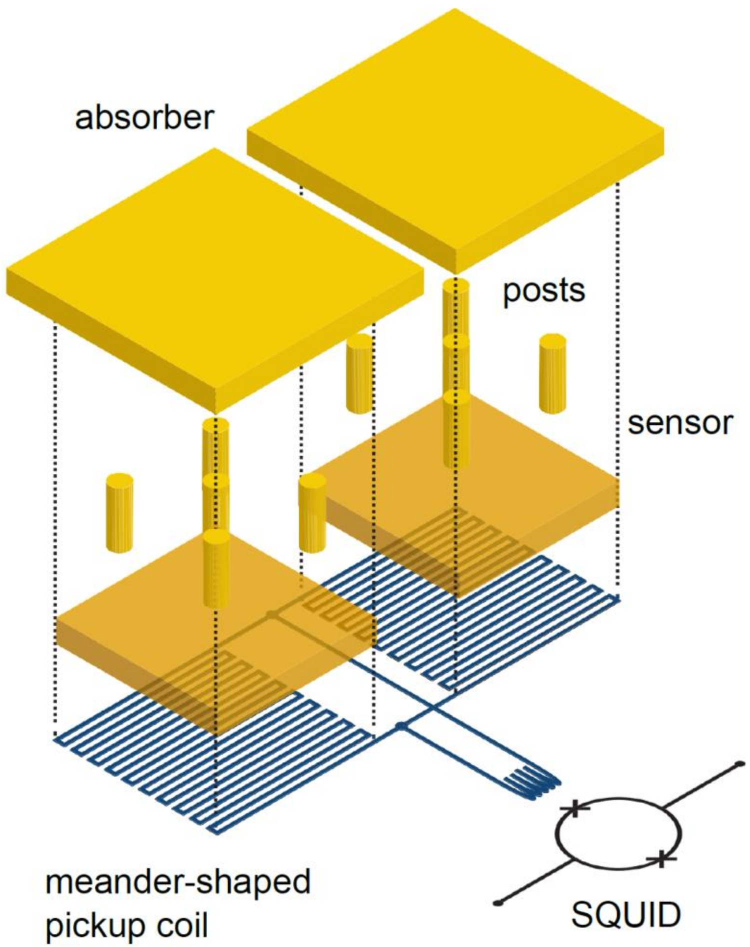
**nuclear physics**
- nuclear isomer state of $^{229}$Th
- nuclear forensics
- nuclear safeguards
- gamma spectroscopy

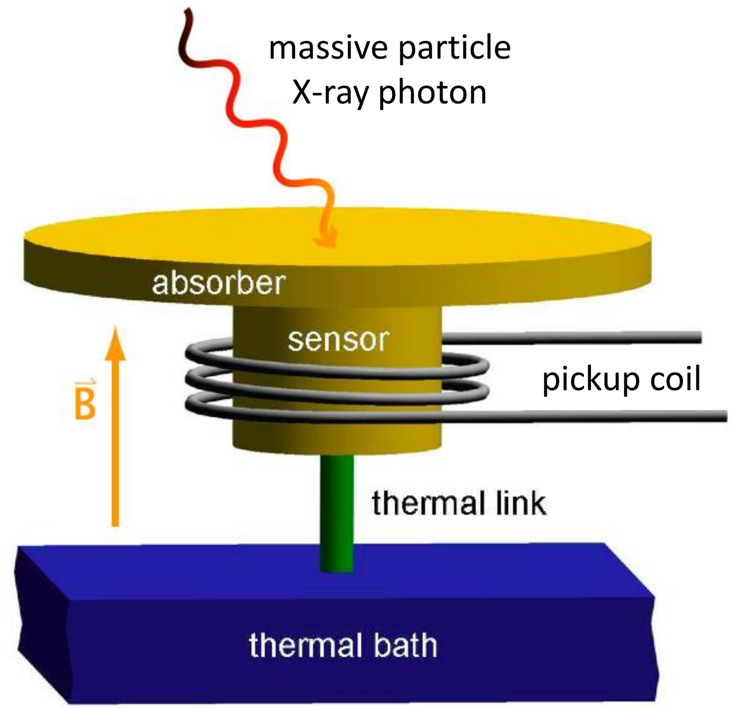
**metrology**
- $\alpha$–, $\beta$–, and $\gamma$–spectroscopy
- Q-value measurements
- measurements of EC spectra

**particle physics**
- neutrino mass determination
- search for $0\nu\beta\beta$
- dark matter searches

# state-of-the-art detector geometries

meander-shaped pick-up coil
(present workhorse)



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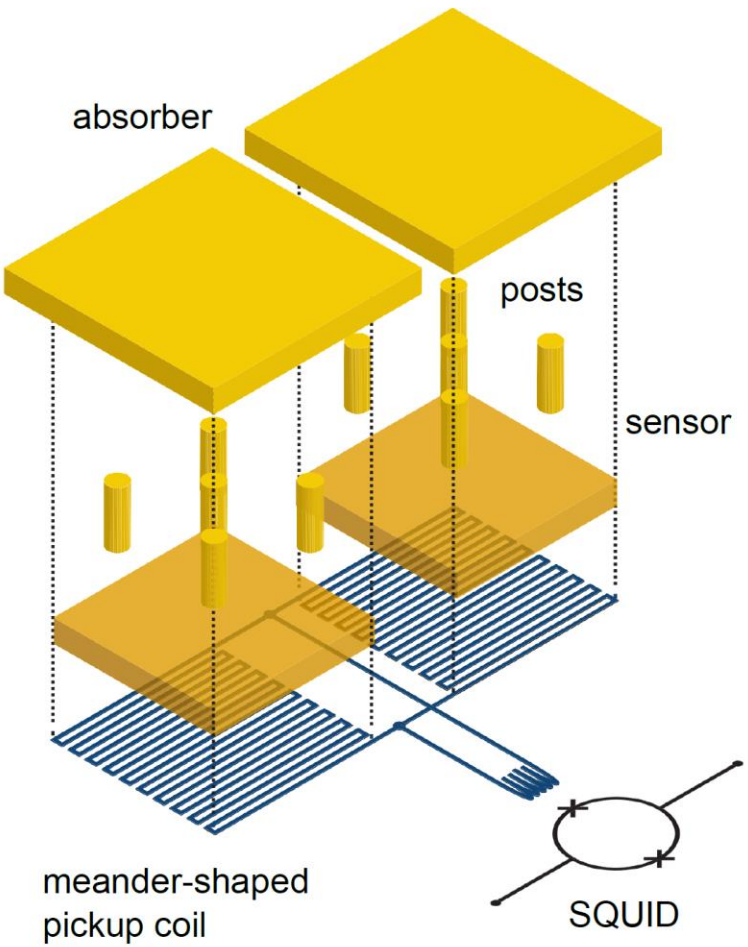
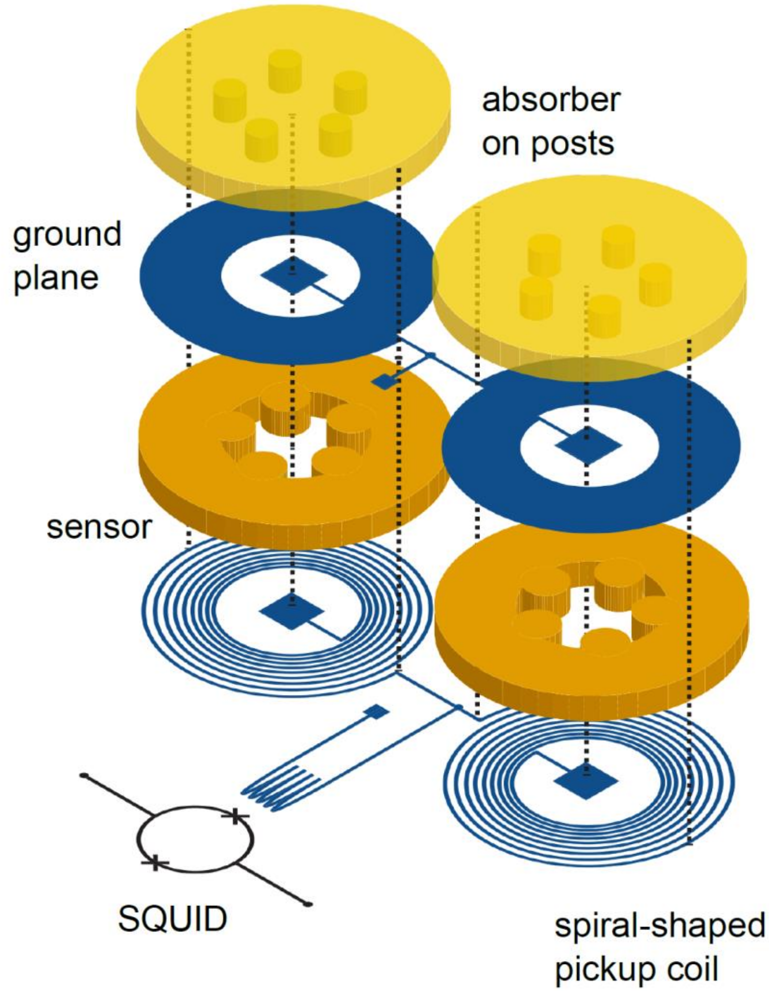



stripline (sandwich) design



# fabrication of metallic magnetic calorimeters

mask writer mask aligner UHV sputtering wet bench chemistry dry etching maskless aligner

- standard UV photolithography
- process with 10 (18) layers

# why dealing with microfabrication?

semiconductor industries operate well-established fabrication facilities (foundries)

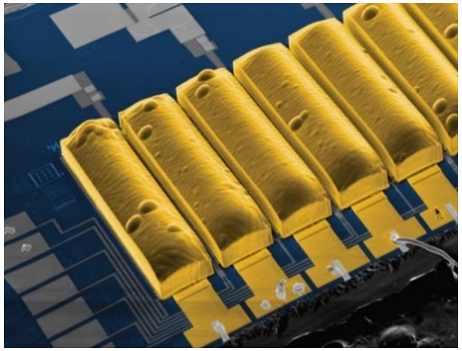
www.intel.com

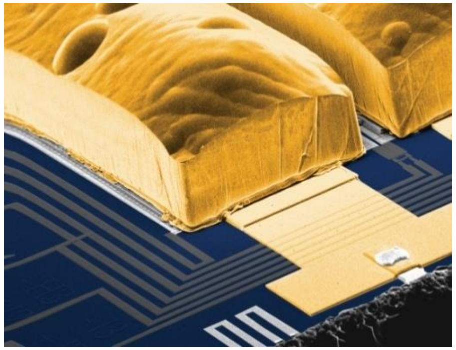
but: MMC + SQUID fabrication requires special fabrication capabilities

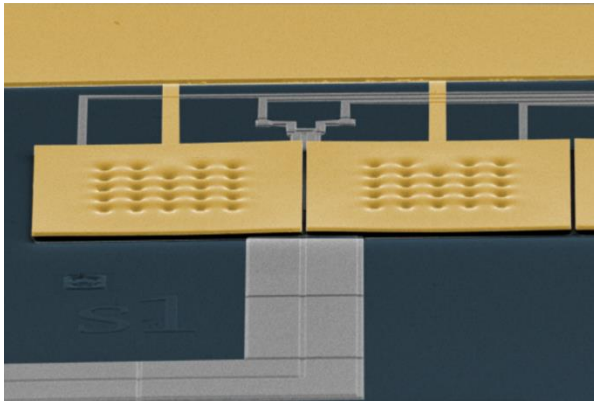
# fabrication of metallic magnetic calorimeters

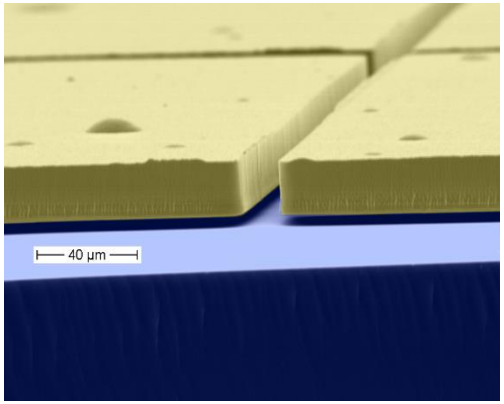
mask writer   mask aligner   UHV sputtering   wet bench   chemistry   dry etching   maskless aligner

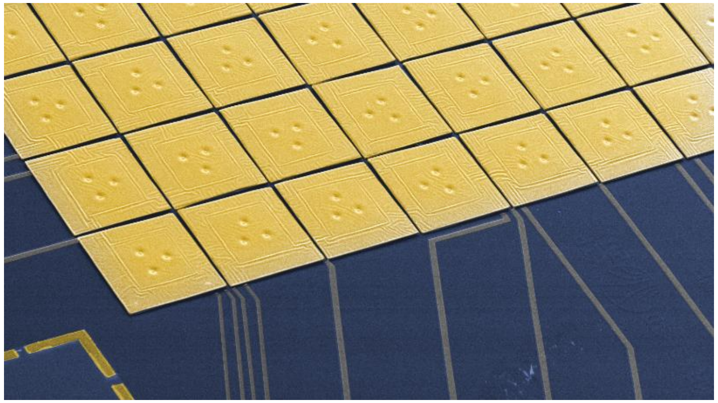
- standard UV photolithography
- Nb based process with 10 (18) layers
- structure sizes: 2 µm – 5 cm
- layer thicknesses: 2 nm – 200 µm
- non-conventional processes, materials





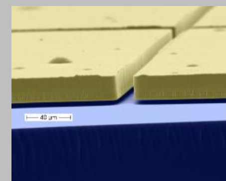




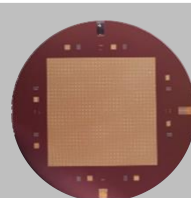
# ‚non-standard' microfabrication portfolio for fabricating MMCs

overhanging particle absorbers

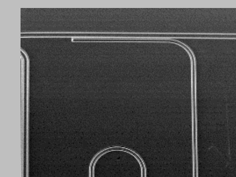


special materials (Nb, Met:Er, ...)

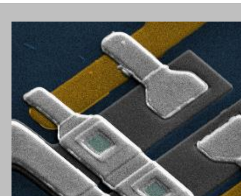
large area structures



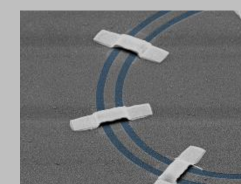
superconducting microwave circuits



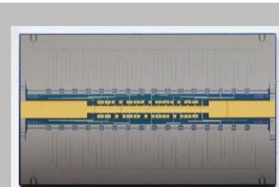
Josephson junction technology



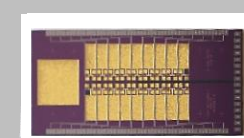
superconducting airbridges



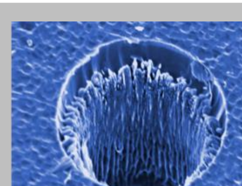
integrated devices



single chip post processing



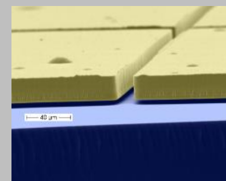
thru substrate vias



and many more

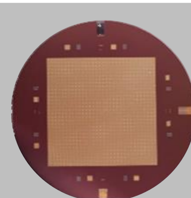
# ‚non-standard‘ microfabrication portfolio for fabricating MMCs

overhanging particle absorbers



special materials (Nb, Met:Er, …)

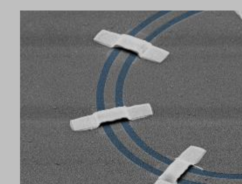
large area structures



superconductin… microwav…

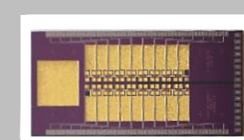
Josephson junction technology

…nducting …bridges

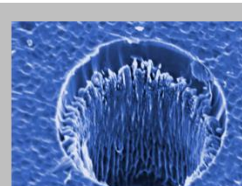


in…

single chip post processing



thru substrate vias



and many more

**highly customized/specialized cleanroom infrastructure and processes required**

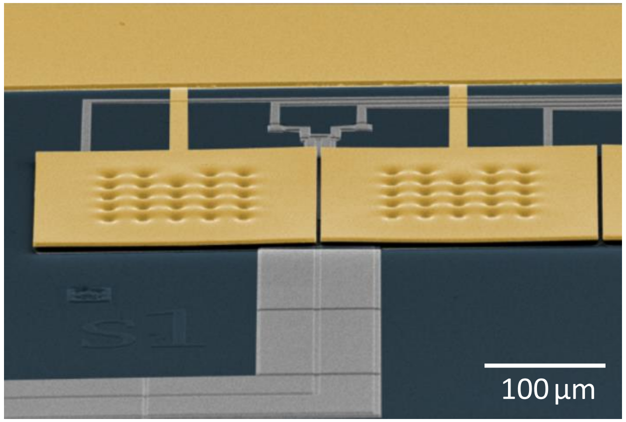
# example: process description for ‘standard’ soft X-ray detectors

detectors with meander-shaped pickup coils and not including thru-substrate vias

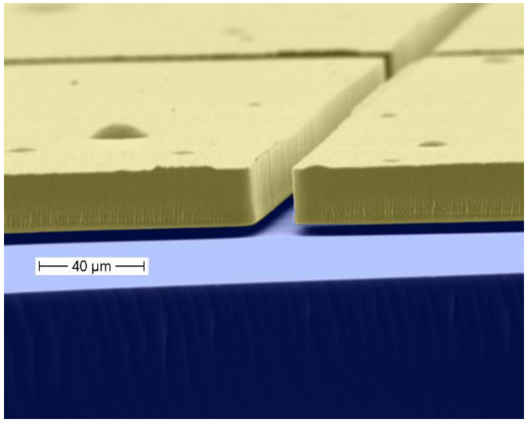
| layer no. | layer name | material | thickness (nm) | process | purpose |
|---|---|---|---|---|---|
| 1 | Nb1 | Nb | 250 | sputtering + RIE | pickup coil, wiring |
| 2 | Iso1a | $Nb_2O_5$<br>$SiO_2$ | 50<br>175 | anodization<br>lift-off + sputtering | insulation |
| 3 | Iso1b | $SiO_2$ | 175 | lift-off + sputtering | insulation |
| 4 | AuPd | Nb / AuPd / Nb | 2 / 160 / 2 | lift-off + sputtering | resistors |
| 5 | Nb2 | Nb | 500 | lift-off + sputtering | wiring |
| 6 | Therm | Nb / Au | 2 / 200 | lift-off + sputtering | detector thermalization |
| 7 | Sens | Nb / Au:Er / Au | 2 / 1300 / 200 | lift-off + sputtering | temperature sensor |
| 8 | Seed | Nb / Au / Nb | 2 / 200 / 50 | sputtering + ion milling + RIE | seed layer for electroplating |
| 9 | Abs | Au | 5000 | electroplating | particle absorber |

# overhanging (free-standing) absorbers

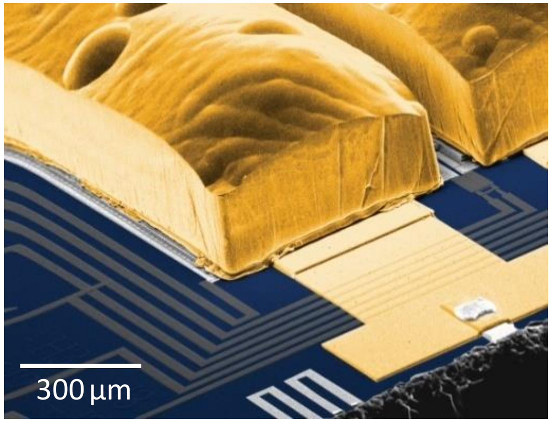
5 µm thick absorbers




15 µm thick absorbers

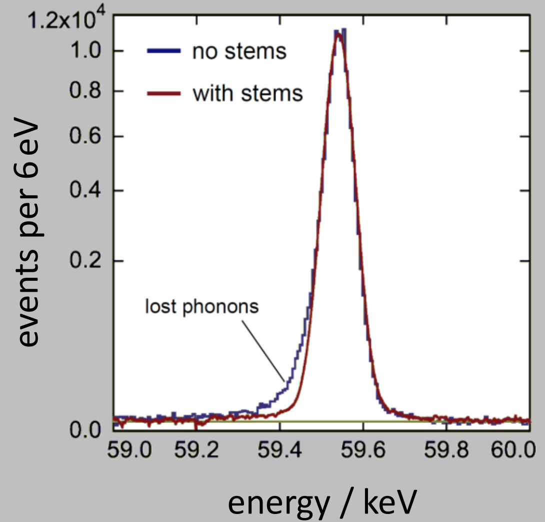



200 µm thick absorbers



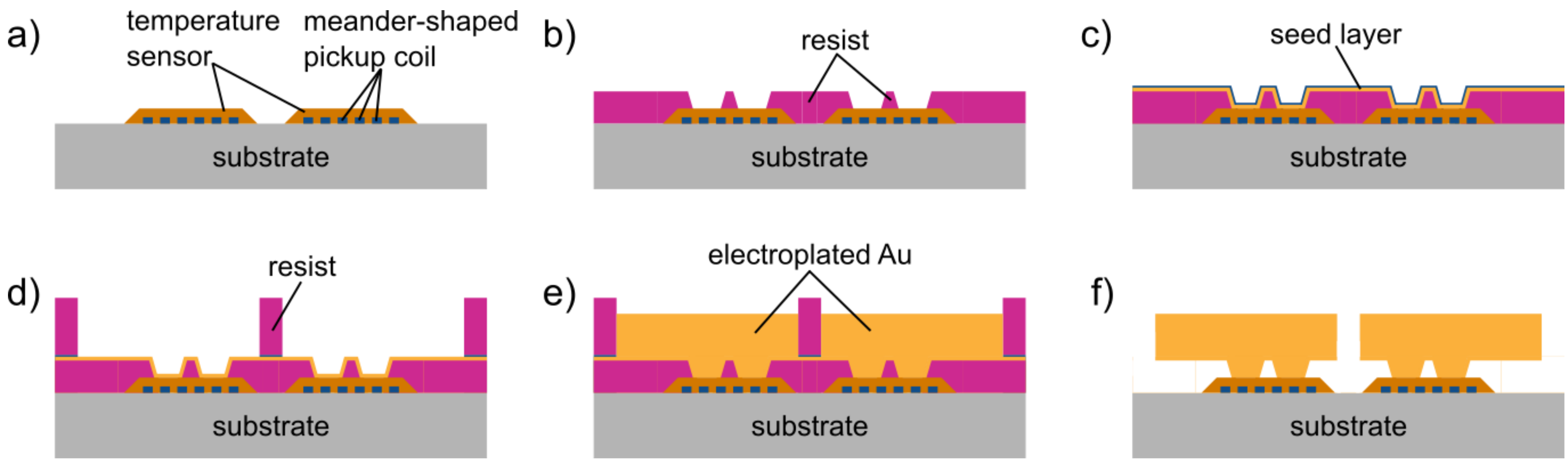

more efficient use of space on chip

reduction of athermal phonon loss



# fabrication of overhanging (free-standing) absorbers

process based on two subsequent resist layers (positive/negative)
that are stacked onto each other



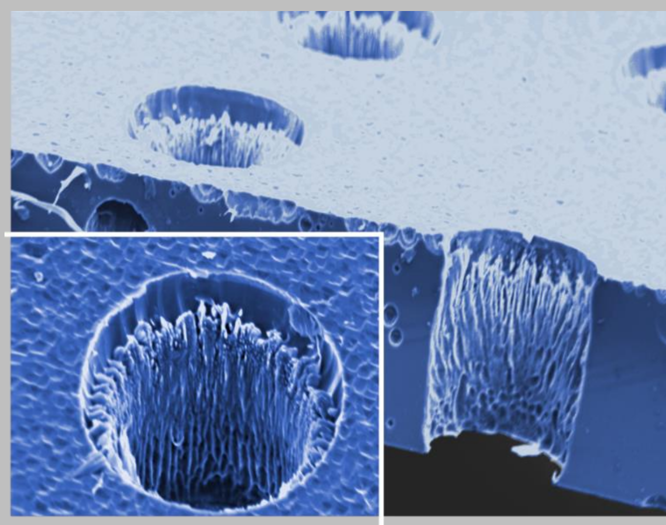

challenges (selection):

- resist aspect ratio: 1:100
- structured resist immersed into chemicals
- resist intercompatibility
- absorber area / support structure area

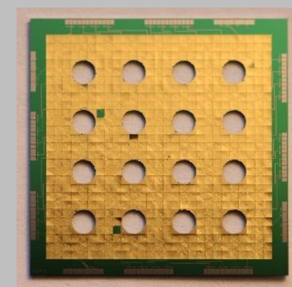
| | |
|---|---|
| AZ nLOF2070: | $h < 7\,\mu m$ |
| AZ 15nXT: | $h < 15\,\mu m$ |
| AZ 125nXT: | $h > 15\,\mu m$ |
| AZ 6632: | $h < 5\,\mu m$ |

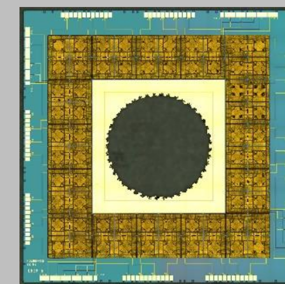
# vertical interconnect accesses (vias) through the substrate

deep reactive ion etching (DRIE)
to make holes through the substrate

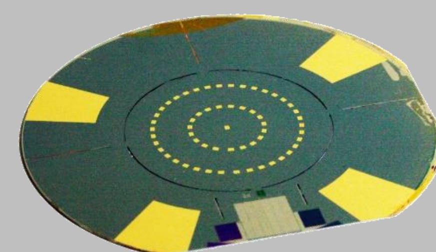


allow particles to fly through the substrate

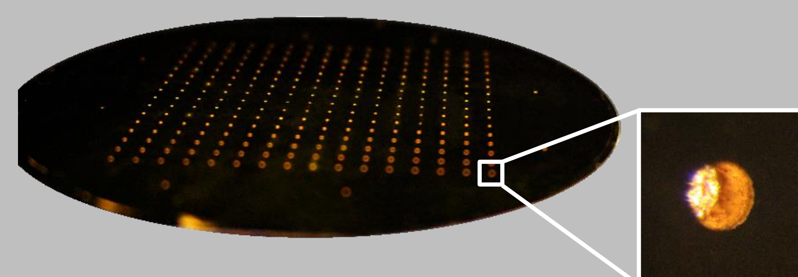




thermal isolation of sensitive detector parts

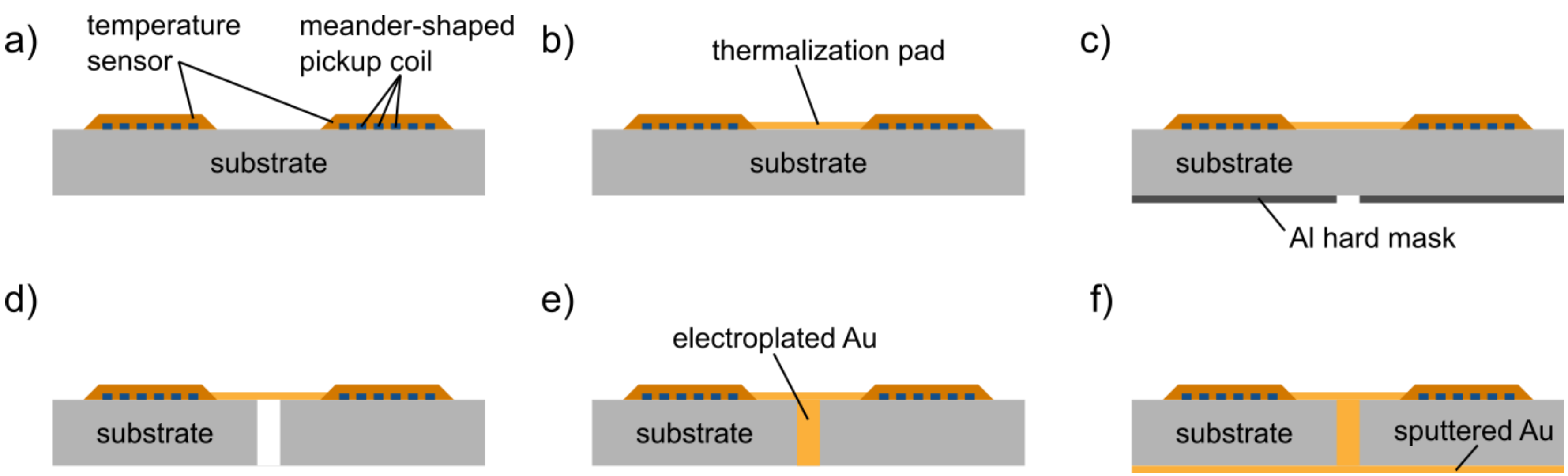


creation of metallic vias through the substrate



# fabrication of through substrate vias

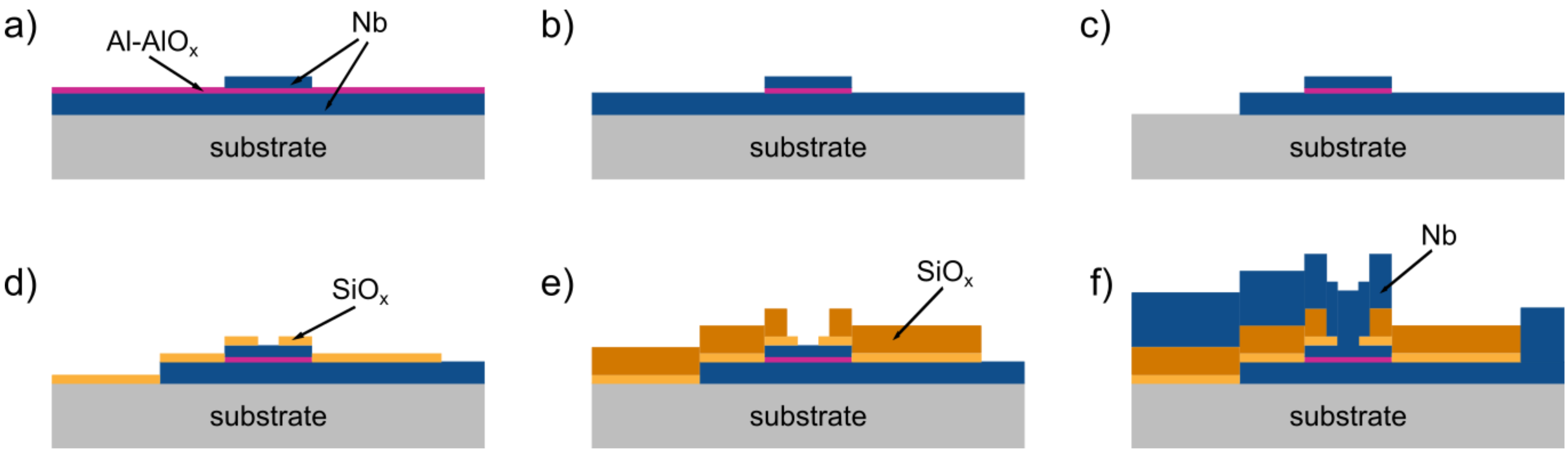
wafer backside processing with Al hard mask technique and DRIE




big challenge: wafer frontside contains almost finished detector

# fabrication of Josephson junctions

in-situ deposited Nb/Al-AlOx/Nb trilayer with selective niobium etching (SNEP)

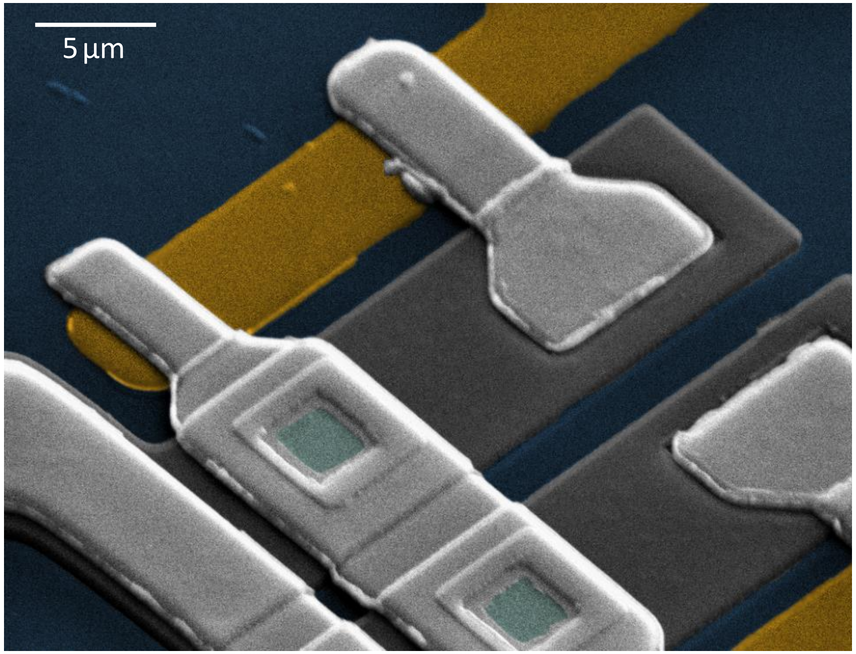


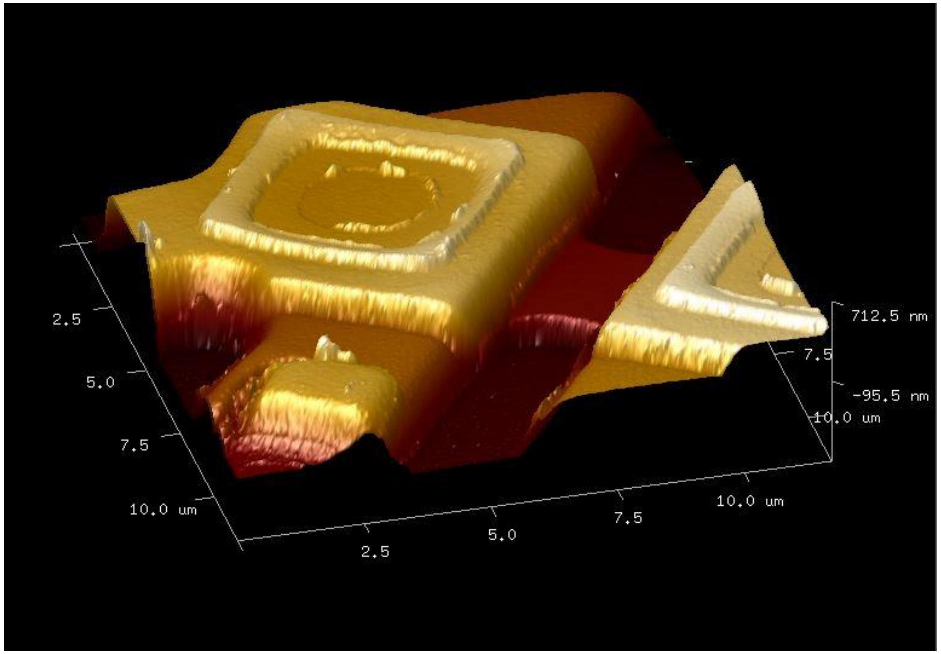

challenge: control of an angstrom thick oxide layer

S. Kempf *et al.*, Supercond. Sci. Technol. **26** (2013) 065012

# fabrication of Josephson junctions

in-situ deposited Nb/Al-AlOx/Nb trilayer with selective niobium etching (SNEP)




presently: smallest junction size (~3 µm) set by size of insulation window (~2 µm)
challenge: reaching sub-µm lateral size

# microfabrication challenges: a selection

- large contiguous arrays ($A_{det} > 100\,cm^2$, $N_{det} > 10^4$)
- no. of detector for large-scale experiments

- detector yield
- operation at mK temperatures

  → intrinsic film stress, thermal contraction

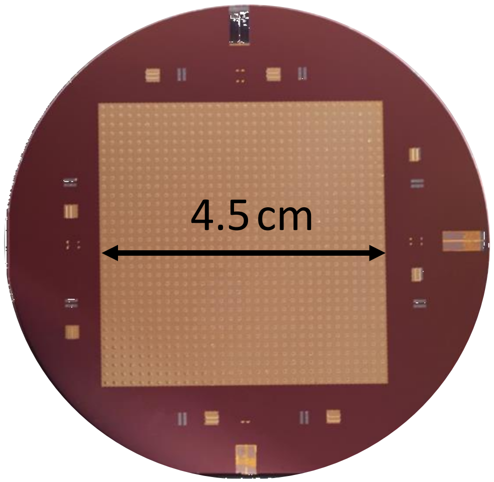
- new sensor / absorber materials

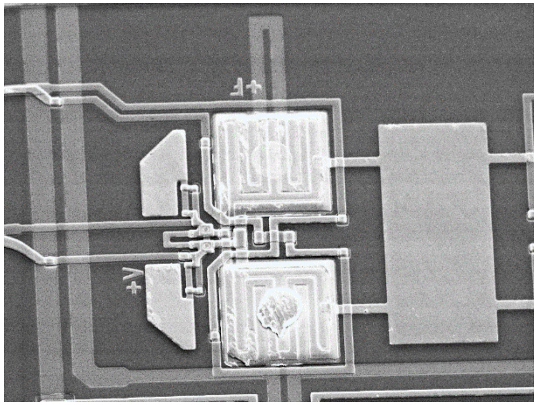
  → Ag:Er, Au/Bi, …

- control of surface morphology, film growth

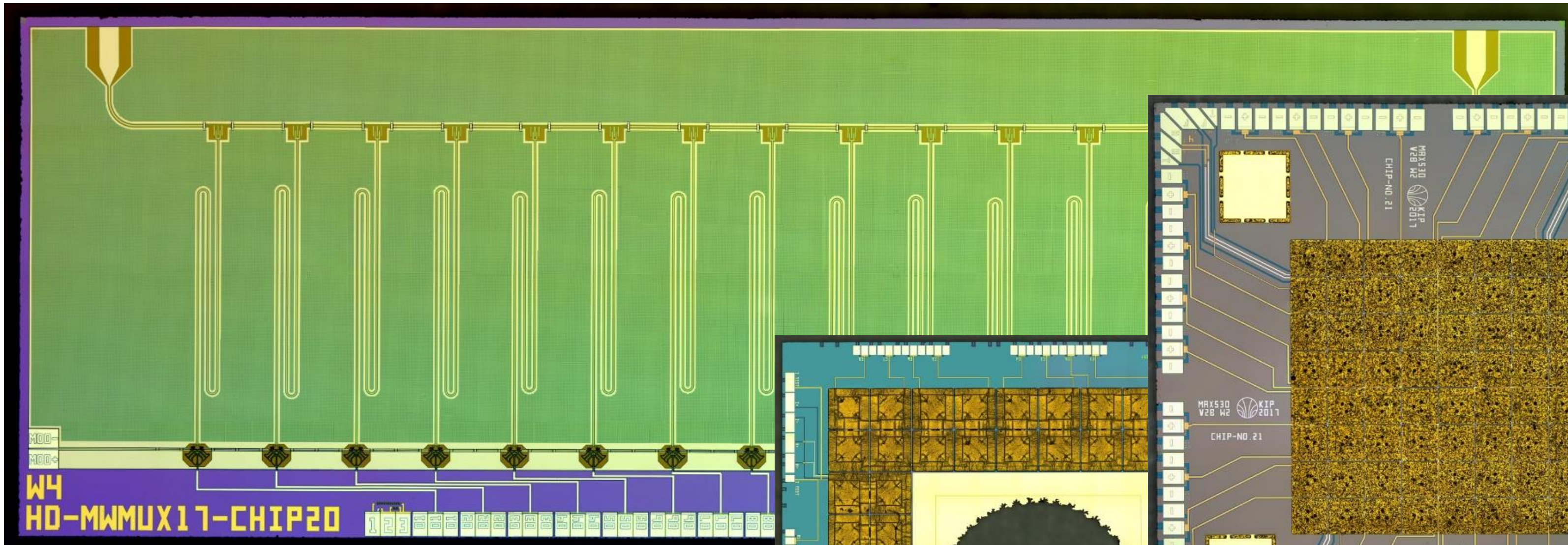
- detector complexity
- no. of wiring layers

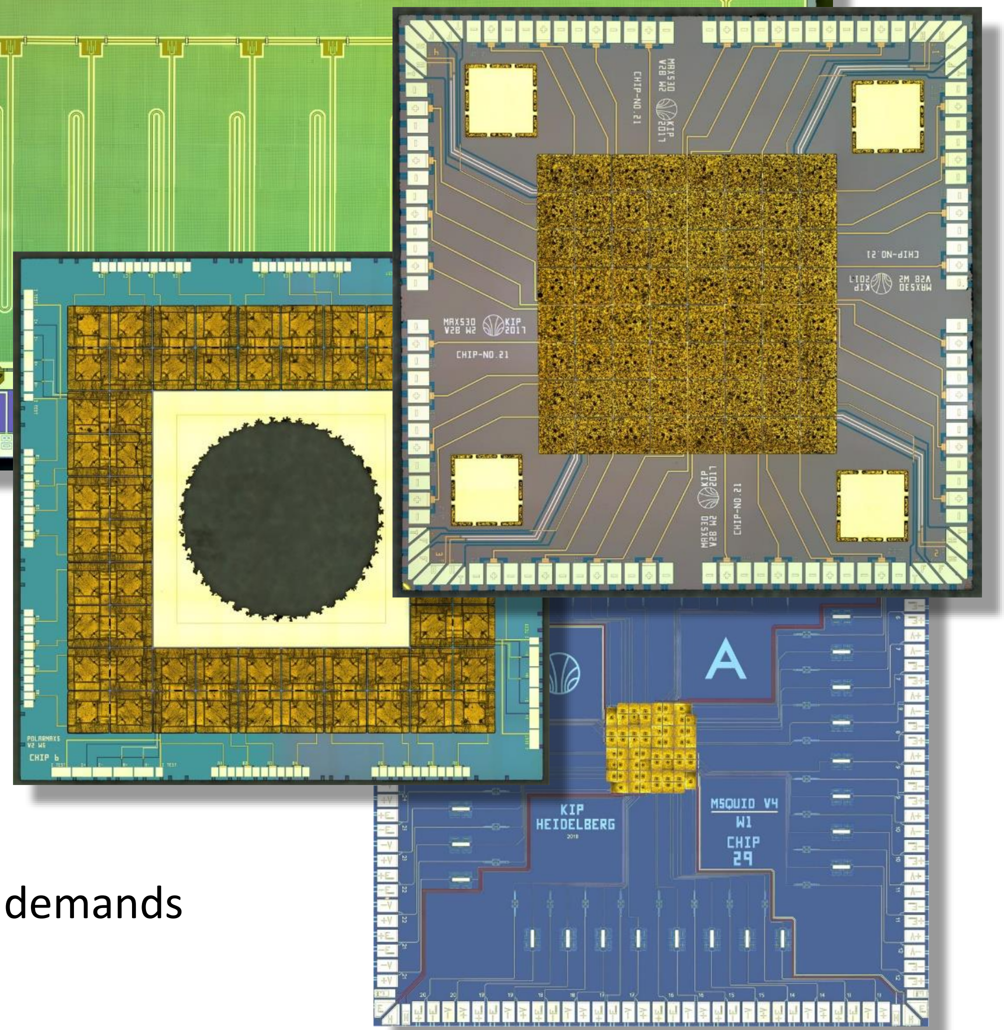
  → planarization (CMP, Nb embedding, …)



# summary




microfabrication of MMCs and SQUIDs
reliabliy works but requires
continuously improvements to address demands
of next-generation experiments

thank you for your attention!