245rd ECS Meeting – Honolulu HI Electromagnetic coils for a 3000 psi hydraulic MEMS valve assembly

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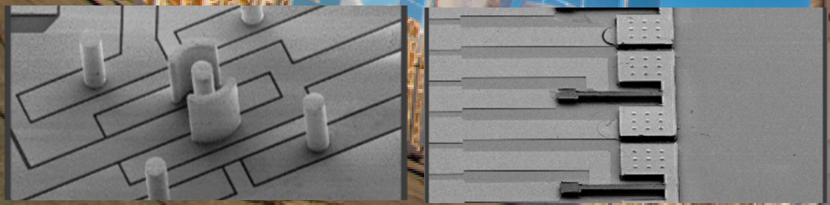

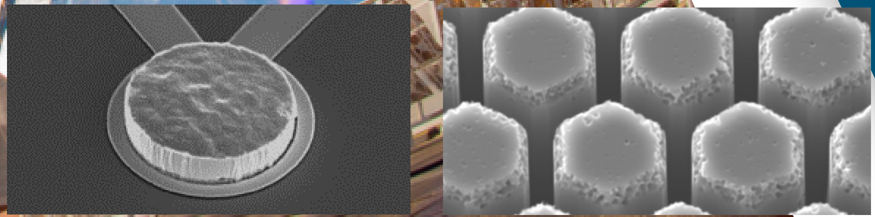

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Motivation

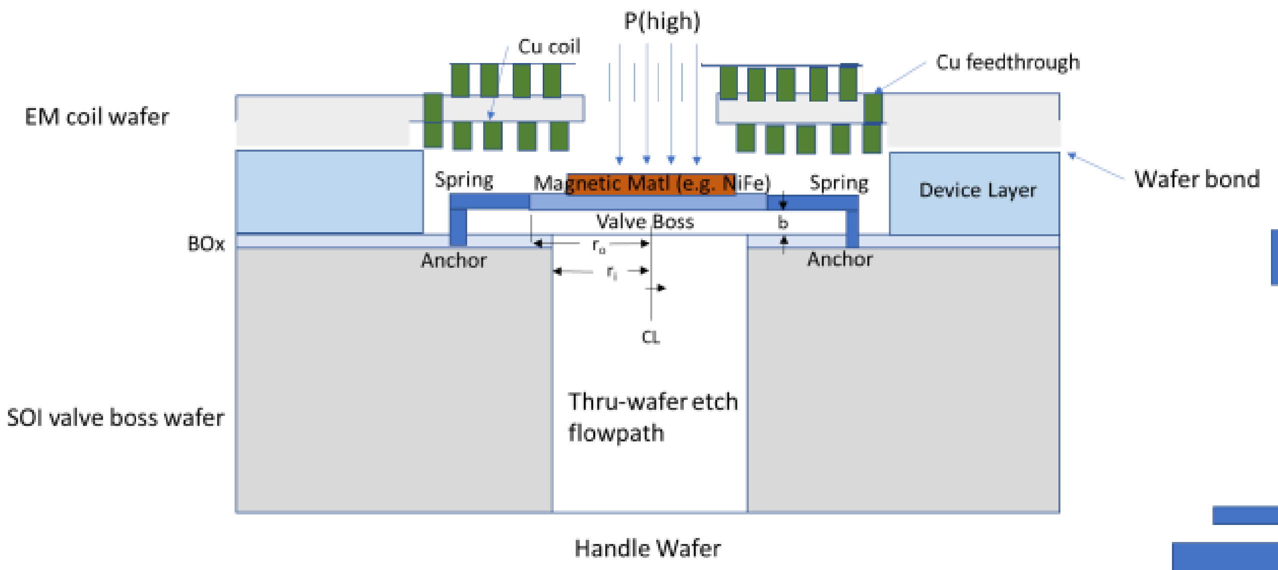
- Fluid powered systems consumed between 2.0 and 2.9 Quadrillion (1015) Btus (Quads) of energy per year; producing ~310-380 million metric tons (MMT) of Carbon Dioxide (CO2).
- Energy efficiencies are 9% to 60% (depending upon the application) average of 22%.
- The US consumes about 100 quadrillion BTU's per year. Fluid power industry accounts for about ¾ per year. Efficiency is typically under 20% (a lot of it is due to the valves). [1]
- If this works, you could easily save 1 quad/yr (this is 1% of the US energy consumption, about $20B/yr in energy costs).
- Compact hydraulic MEMS valve takes advantage of scalable semiconductor fabrication capable of integrating 1000's of pressure valves together
- Enable hydraulic and gas based MEMS valve devices

[1] Estimating the Impact (Energy, Emissions and Economics) of the U.S. Fluid Power Industry, ORNL/TM-2011/14, Love

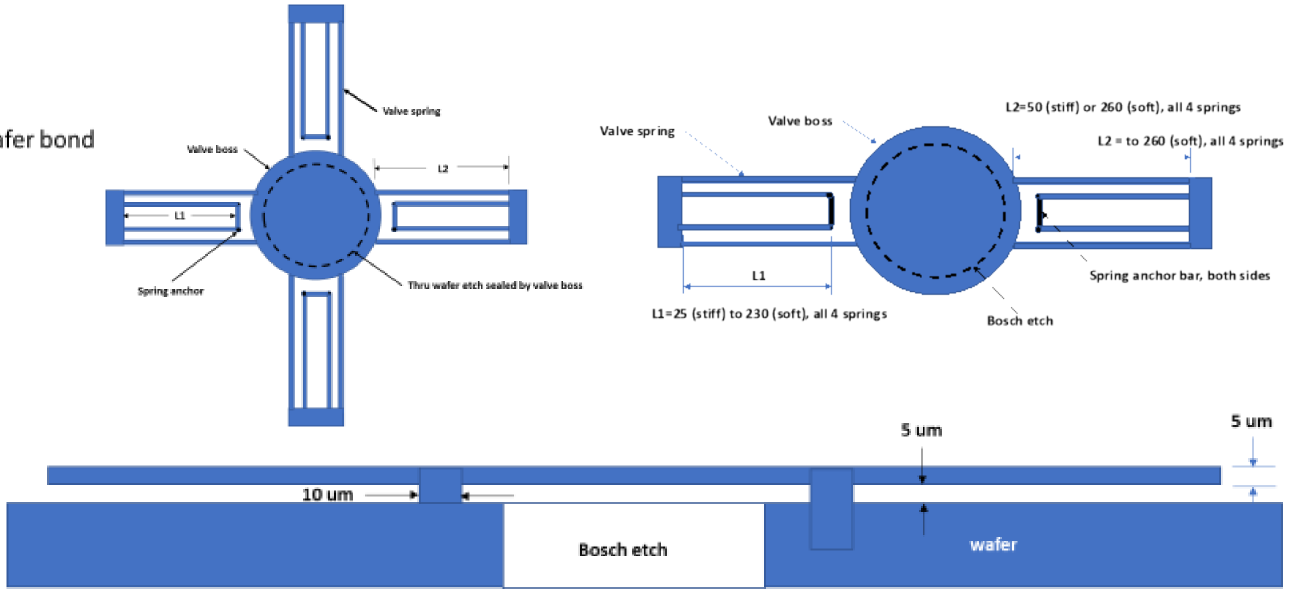
MEMS valve assembly

- High pressure (3000 psi) pushes valve boss down sealing thru-wafer via (normally closed valve).
- MEMS coil with current pulls valve boss up, opening the flow path and allowing flow from above the EM coil wafer around the valve boss and through the handle wafer
- A 2nd Cu coil layer on top could double the EM force.

Double coil



Top view and cross section view of 2 & 4 leg MEMS springs



Balance coil fabrication and performance

- Balance valve performance, size, & power with MEMS fabrication capability
- 18 ml/min when open, 3000 psi pressure across valve when closed (normally closed), 30 μm radius valve orifice
- GEN 1 designs, 5 micron gap to move boss valve, 5 coil turns,
    - 1)10 um wide traces with 10 um gaps, 50 um inner radius, 20 um thick, N=5 turns (1 amp, F ~ 0.04 mN, 10 amps, F ~ 4 mN)
    - 2)20 um wide traces with 20 um gaps, 25 um inner radius, 40 um thick, N=5 turns (1 amp, F ~ 0.042 mN, 10 amps, F ~ 4.2 mN)

Pressure force:

$$F_p = P \times A = (2.04\times10^{7})\left(\pi\cdot(30\times10^{-6})^2\right) = 0.0577\,N = 57.7\,mN$$

Magnetic Field generated

$$\bar{B} = \left(\frac{\mu_0}{2}\right)\cdot\left(\frac{N\cdot i}{r}\right) \sim 0.66\,T$$

N = 5 (number of turns), design selection

F_{EM} = 0.0577 N, equal to pressure force

$\mu_0 = 4\pi \times 10^{-7}$ N/m, magnetic permeability of air/vacuum (hydraulic fluid is similar)

A = coil area (πr_{coil}^2), select coil inside radius slightly larger than the valve boss radius

Coil radius (r_{coil}) = r_i + olap + offset = 30 + 10 + 10 = 50 μm. Therefore $A_{coil} = \pi\,(50 \times 10^{-6})^2 = 7.85e\text{-}9\ m^2$.

g = b + offset = 5.45 + 5 = 10.45 μm

EM force and current required.

$$F_{EM} = 0.0577\,N = \frac{(Ni)^2\cdot\mu_0\cdot A}{2\cdot g^2}$$

Valve gap calculation:

Q = 18 ml/min (3e-7 m^3/s), design point flow requirement

μ = 0.02 N-s/m^2, viscosity of a representative hydraulic fluid

ΔP_{gage} = 3000 psi (2.04e7 N/m^2)

r_i = 30 μm

$r_0 = r_i$ + olap = 30 + 10 = 40 μm

b=5.45 micron

$$b = \left[\frac{Q\cdot 6\mu\cdot\ln\left(\frac{r_o}{r_i}\right)}{\pi\cdot\left(\Delta P_{gage}\right)}\right]^{1/3}$$

Current needed

$$i = \sqrt{\frac{F_{EM}\cdot 2\cdot g^2}{\mu_0\cdot A\cdot N^2}}$$

N = 5 (number of turns), design selection

F_{EM} = 0.0577 N, equal to pressure force

$\mu_0 = 4\pi \times 10^{-7}$ N/m, magnetic permeability of air/vacuum (hydraulic fluid is similar)

A = coil area (πr_{coil}^2), select coil inside radius slightly larger than the valve boss radius

Coil radius (r_{coil}) = r_i + olap + offset = 30 + 10 + 10 = 50 μm. Therefore $A_{coil} = \pi\,(50 \times 10^{-6})^2 = 7.85e\text{-}9\ m^2$.

g = b + offset = 5.45 + 5 = 10.45 μm Using the equation just above:current(i) ~ 10.45 Amps

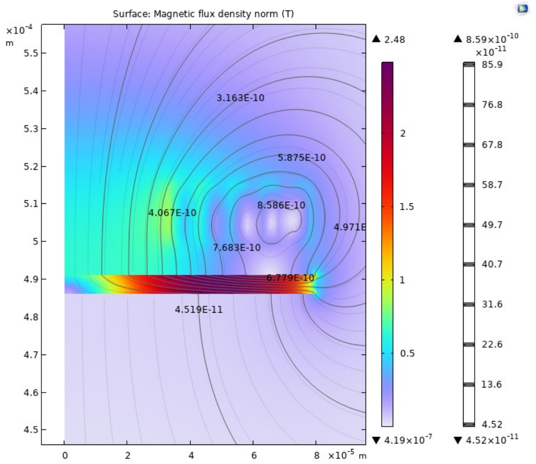
Comsol Model

Gen 1 design, I = 10 Amps → force of 0.0025 – (-0.0025) ~ 0.005 N was calculated by Comsol vs 0.0577 N needed (significantly less than needed, and less than simple calculation).

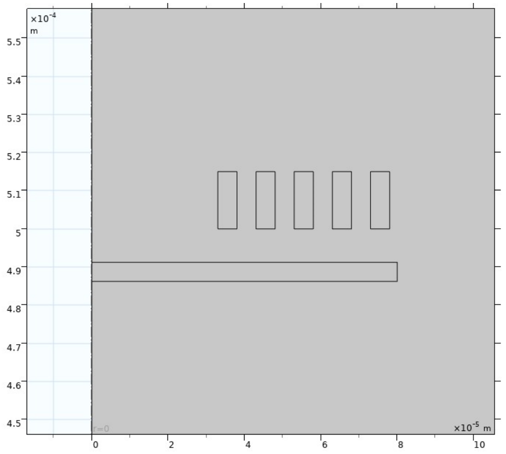
B-field of 2.48 T was calculated inside the Permalloy valve body

B-field at the center of the solenoid ~ 0.75 T (close to Matlab)

B field



Geometry analyzed



Spring design

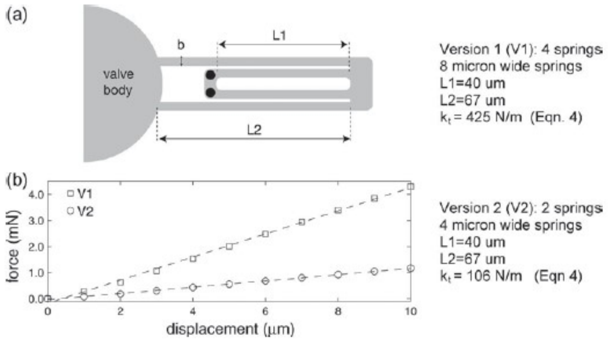
- Springs made from (Permalloy, E = 120 GPa), thickness (b = t = 5 um), width 5 micron, & 2 or 4 identical springs per valve boss
- **a maximum spring force of ~ 5 mN** is desired at full deflection (5 um). $K_{t\text{-}low}$= 0.05 mN/5 um = 5 x 10^{-5} / 5 x 10^{-6} = 10 N/m, k(per spring) = k_t/4 = 2.5 N/m
- **a minimum spring force of ~ 0.05 mN** is desired at full deflection (5 um). $K_{t\text{-}high}$= 5 mN/5 um = 5 x 10^{-3} /5 x 10^{-6} = 1000 N/m, k(per spring) = k_t/4 = 250 N/m

L1 = 25 um & L2 = 50 um: K (per spring) ~ 1 x 10^3 N/m, close enough to the goal stiffness at the very high end that approximately matches a 3000 psi pressure over a 60 um diameter hole.

L1 = 55 um and L2 = 75 um: K (per spring) ~ 255 N/m, close enough to goal stiffness of 250 N/m at the high end.

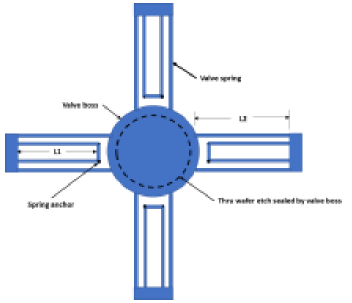
L1 = 100 um and L2 = 120 um: K(per spring) ~ 50 N/m, close enough for an intermediate goal stiffness

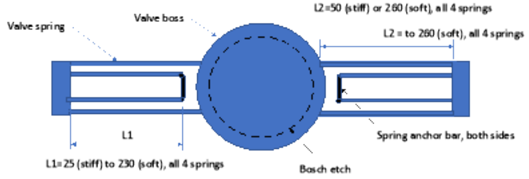
K(per spring) ~ 5 N/m close enough to goal stiffness, to get to 2.5 N/m use only 2 springs. To get even weaker need to reduce thickness.

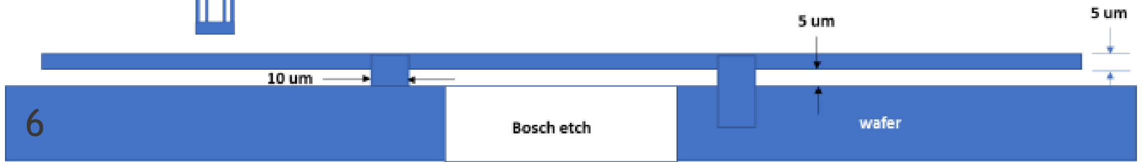


$$k_t = \frac{2 \cdot Ebt^3}{(L_1^3 + L_2^3)}$$

L1(um)	L2(um)	k(per spring) (N/m)	k(4 springs) (N/m)	F(4 springs) N, 10 um deflect
25	50	1000	4000	0.04
55	75	250	1000	0.01
100	120	50	200	0.002
230	260	5	20	0.0002





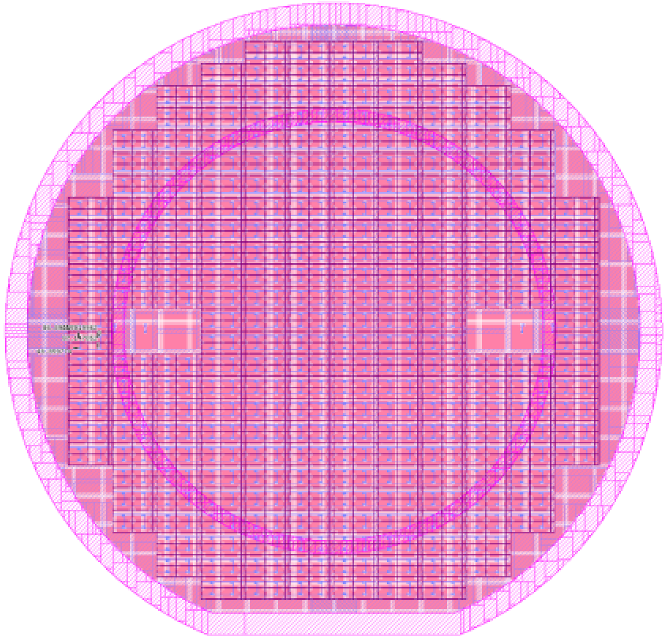


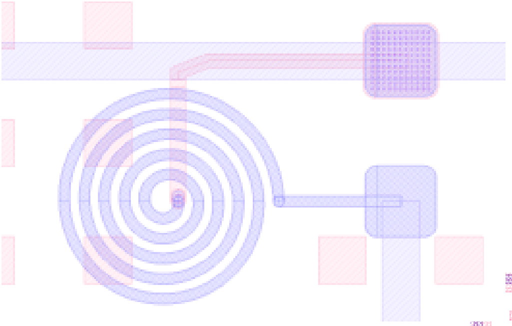
L1(um)	L2(um)	k(per spring) (N/m)	k(4 springs) (N/m)	F(4 springs) N/m, 10 um deflect	F(4 springs) N/m, 5 um deflect	F(2 springs) N/m, 5 um deflect
25	50	1000	4000	0.04	0.02	0.01
55	75	250	1000	0.01	0.005	0.0025
100	120	50	200	0.002	0.001	0.0005
230	260	5	20	0.0002	0.0001	0.00005

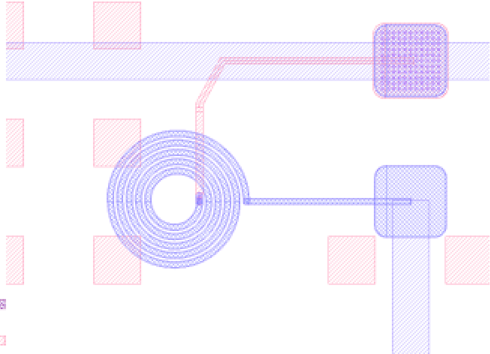
Magnetic Coil Mask Design

- 6 inch wafer
- 4 inch coring available
- 4 coils per die, 60 micron hole, 2 designs each with 5 turns → 10/10 micron coil and 20/20 coil (coil width/spacing)
- 2 micron alignment tolerance from redistribution layer 1 to copper coil plating layer 2
- Bus bar to enable electroplating

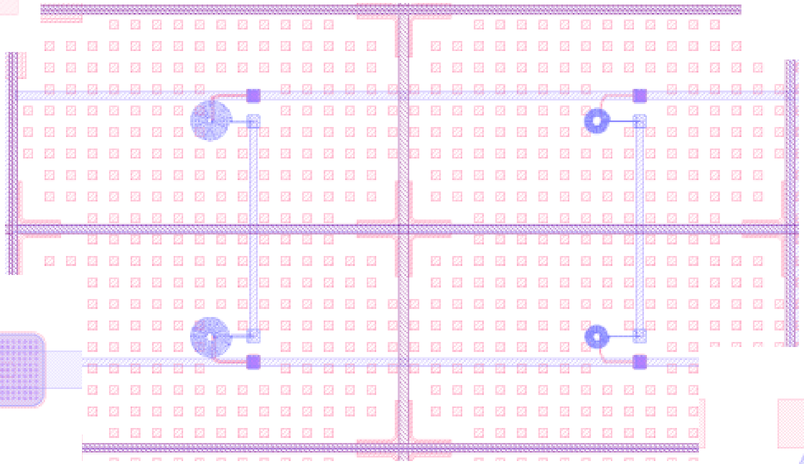
Wafer level



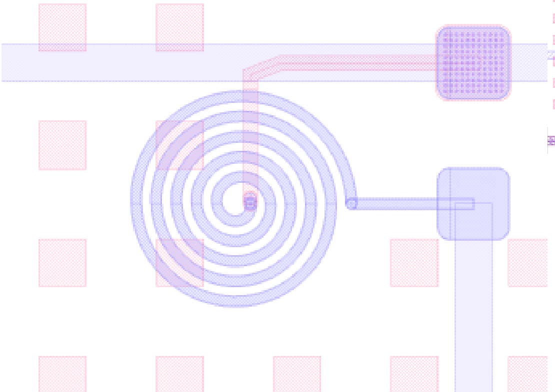


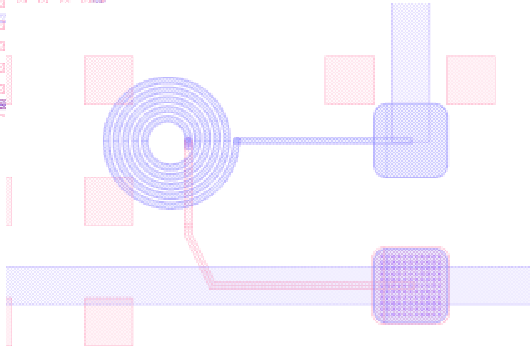


Die level

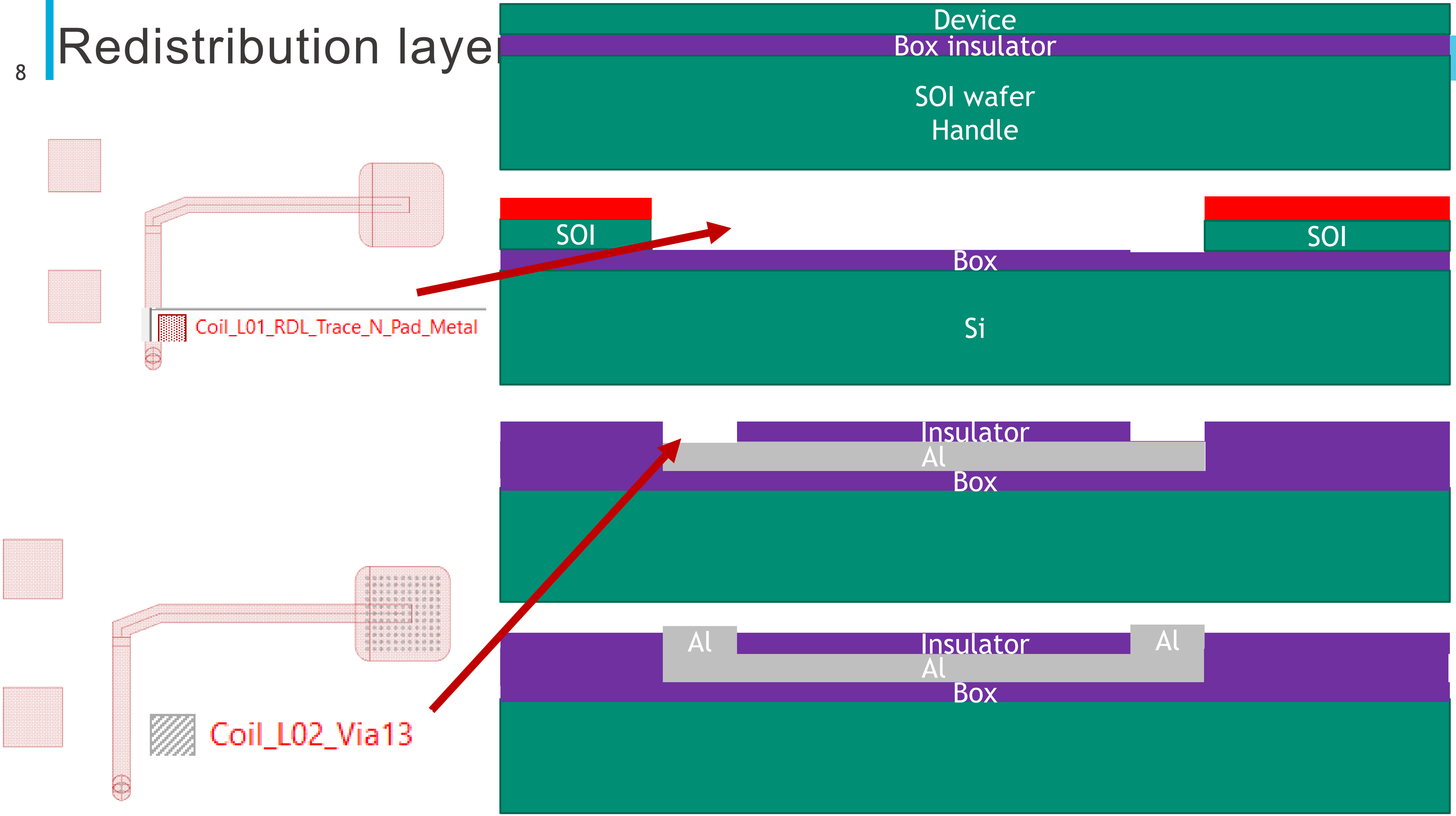


Individual device

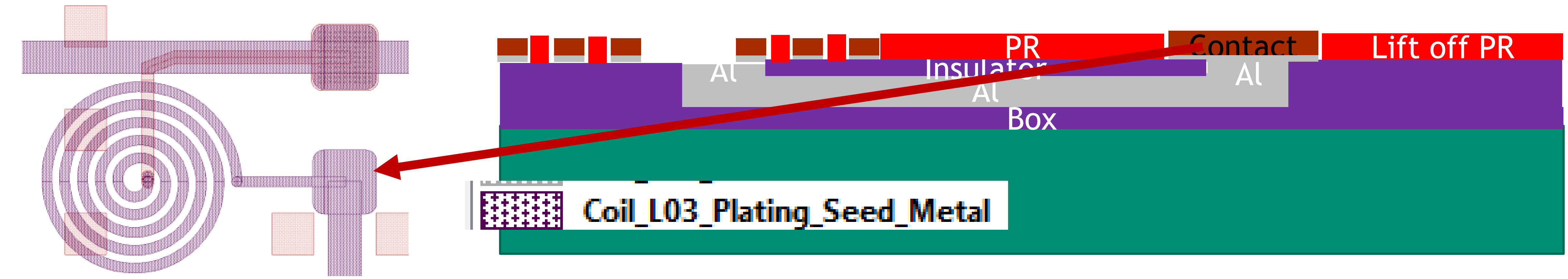


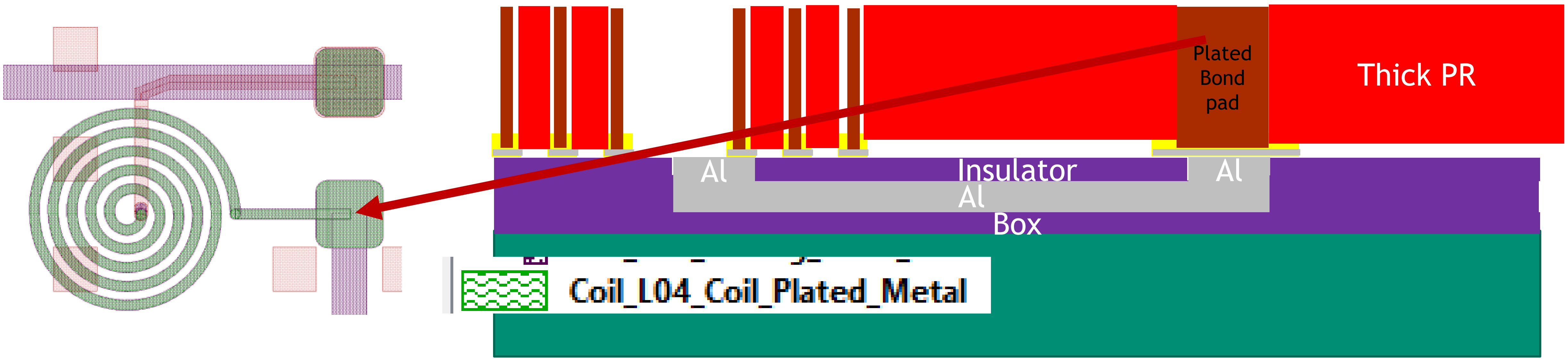


Redistribution layer



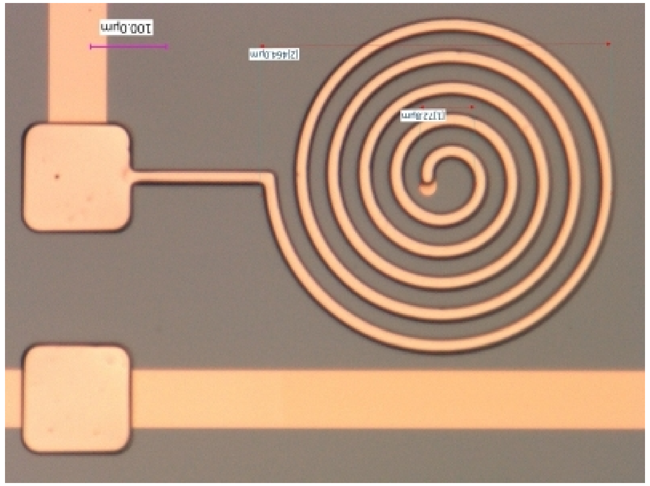
Seed layer with bus bar and copper electroplating

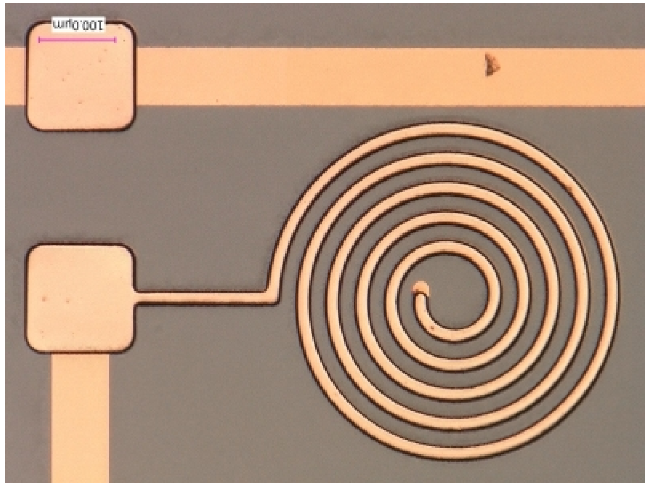




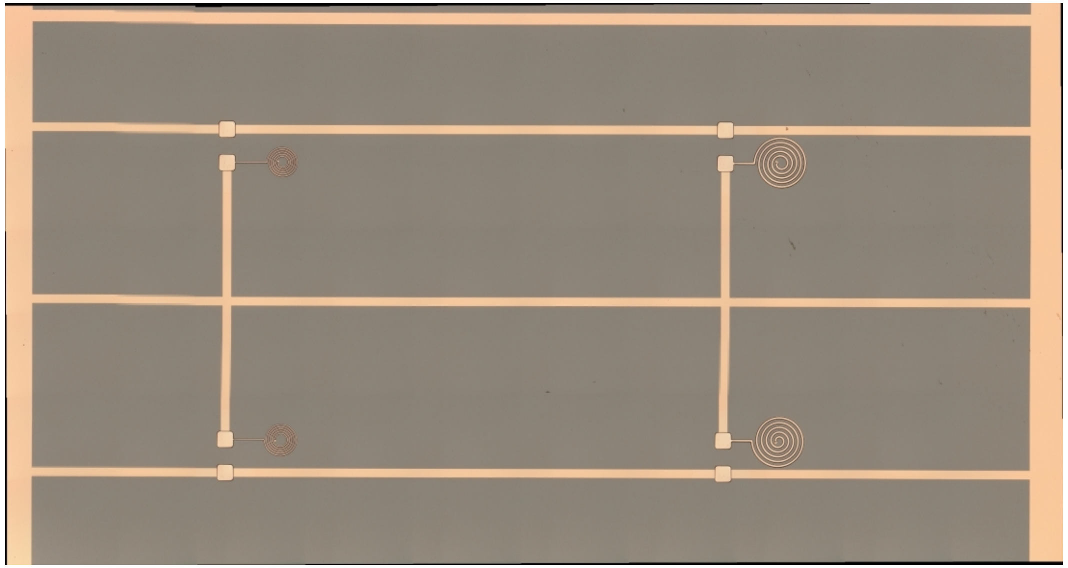
Copper electroplating on test wafer

Individual devices

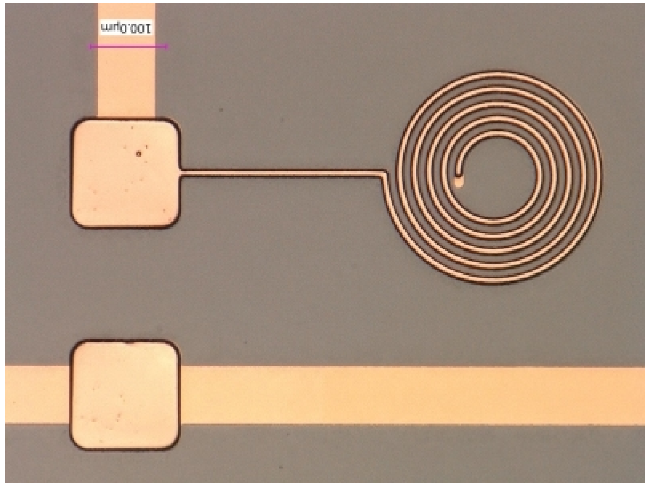


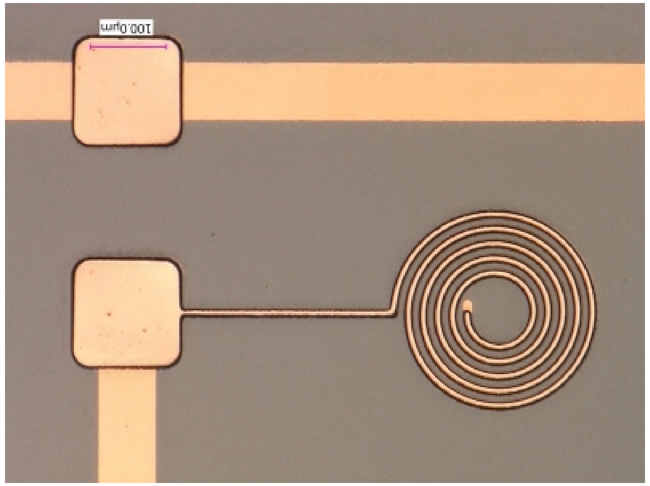


Die level



Individual devices



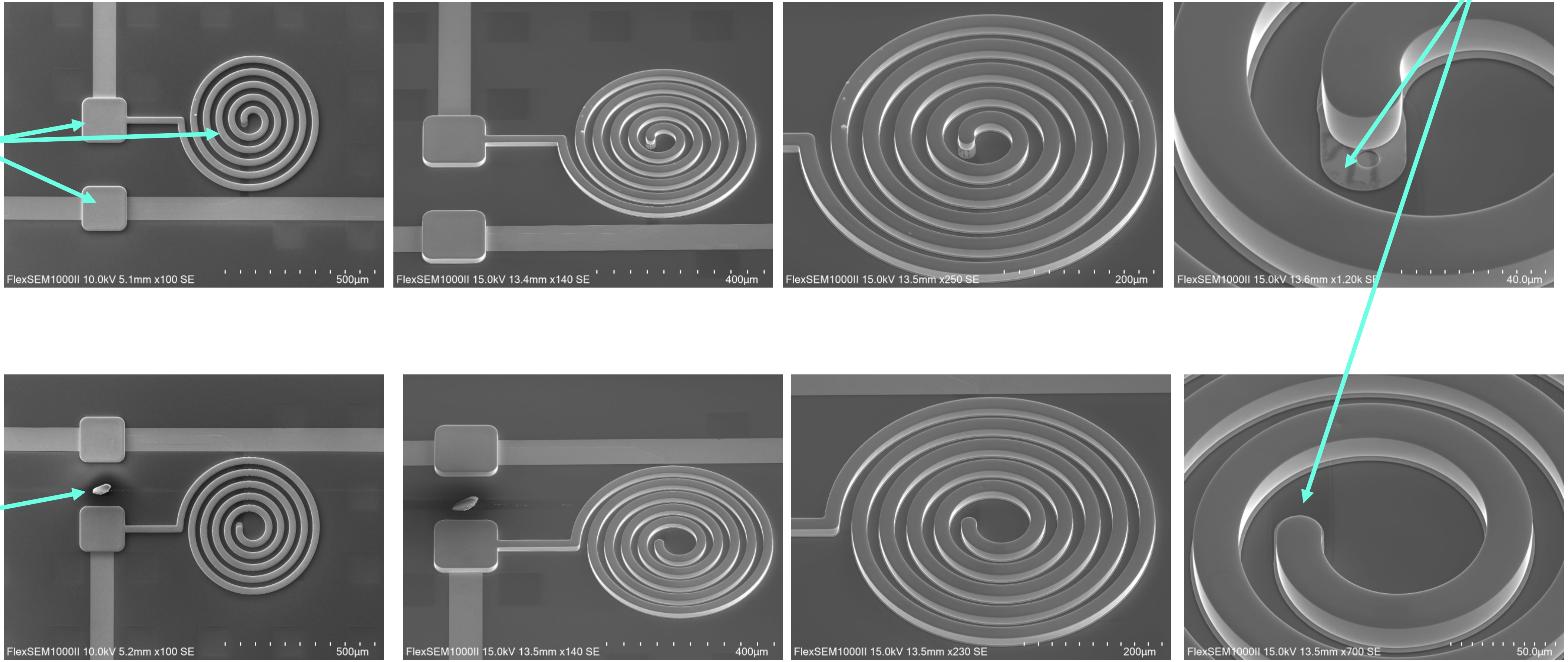


SEM images post copper electroplated devices

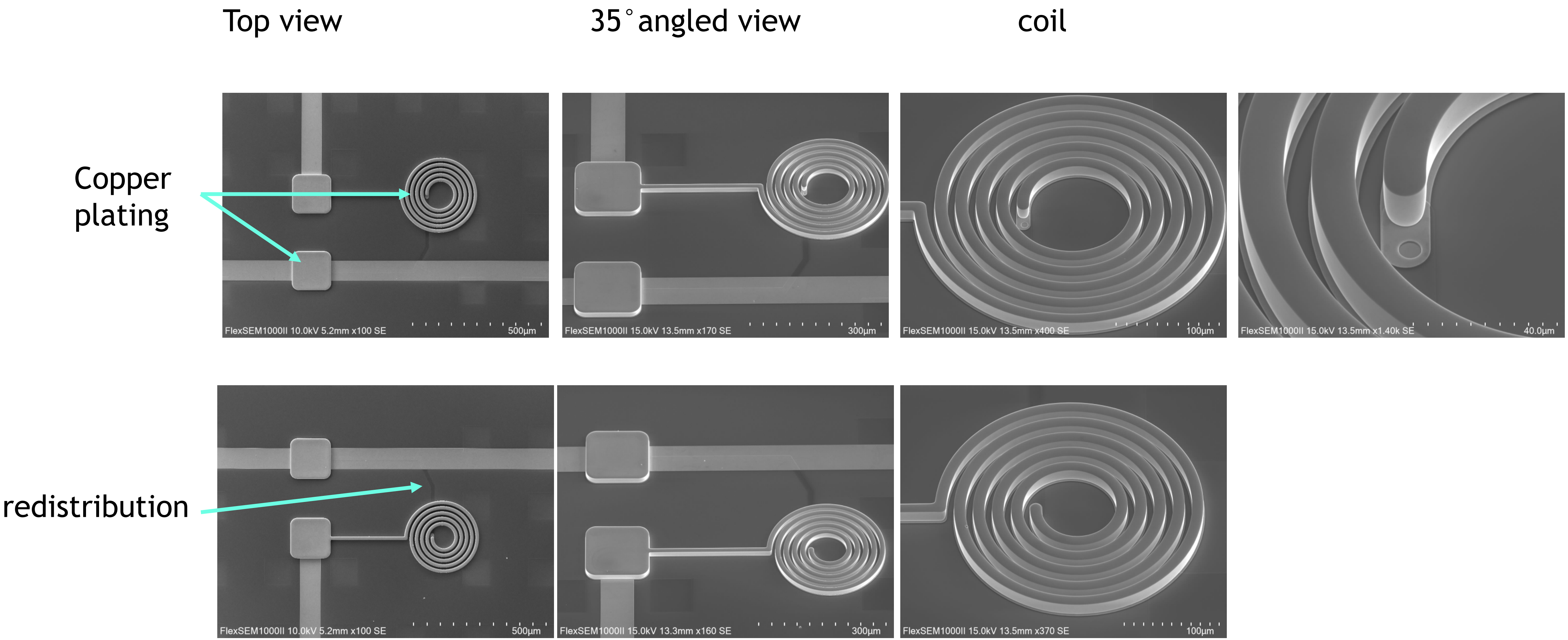
Top view | 35° angled view | coil | redistribution

Copper plating

Dust defect likely from handling

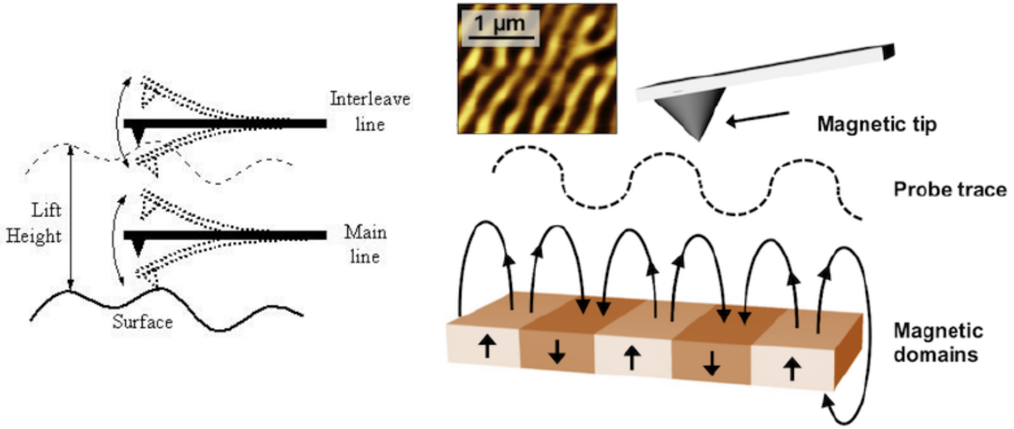


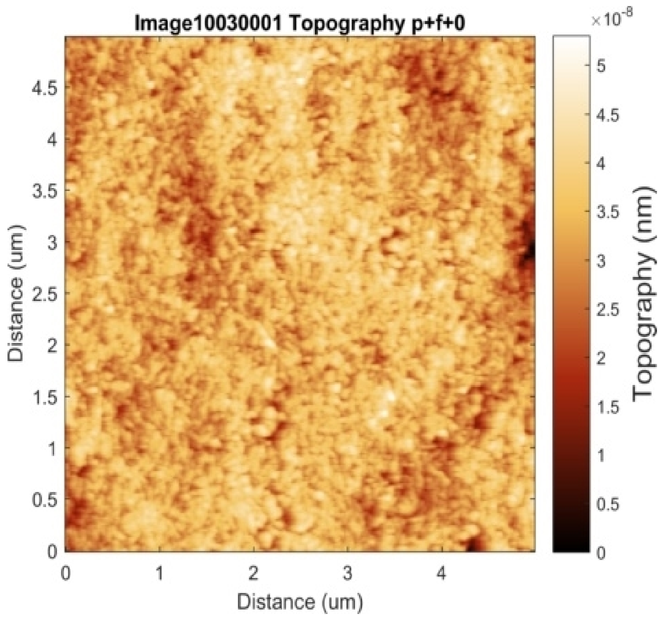
SEM images post copper electroplated devices

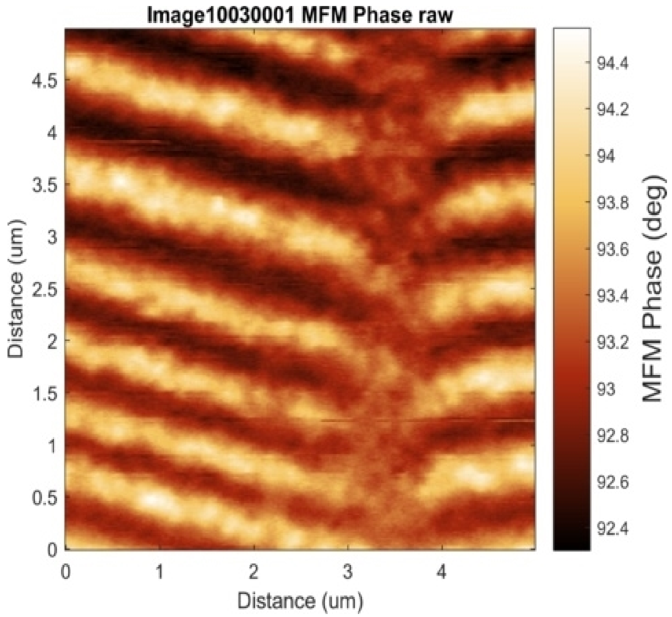


Magnetic AFM testing

- Place card holder for magnetic AFM testing too be done the week of 09/30/2024
- Magnetic tip hovers above surface of coil, when energized the change in magnetic field can seen in a topography map shown

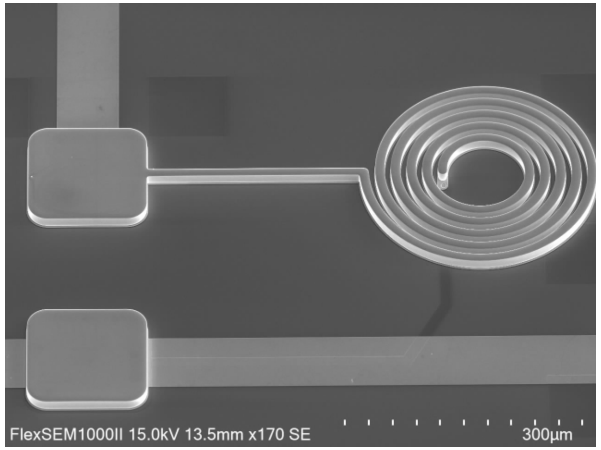


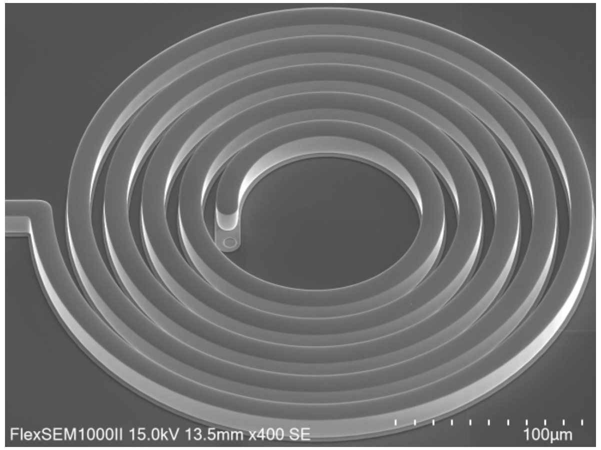


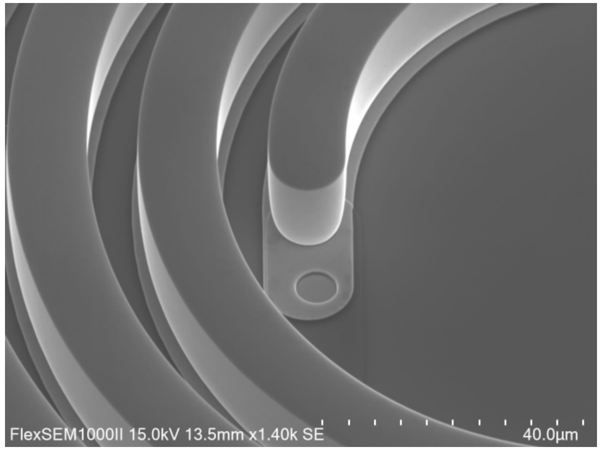


Conclusions

- Designed MEMS based valve assembly targeting 3000 psi
- Created microfabrication flow for magnetic coils
- Fabricated magnetic coils
- Future work:
    - Testing of magnetic coils
    - Integrate boss valve







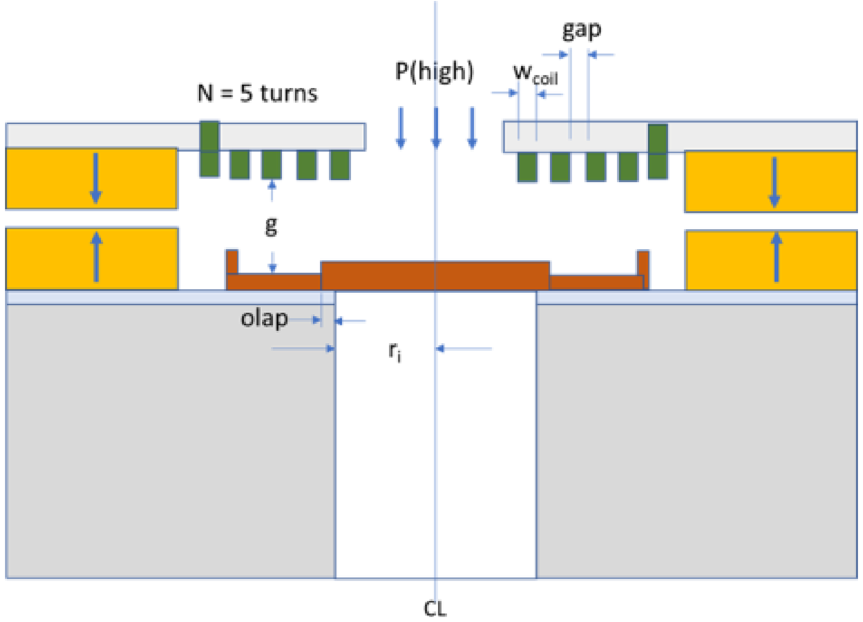
Questions?

Valve/actuator schematics II

- Gold eutectic bond between coil (actuator) and valve wafer/die
- N (number of turns), coil trace width, gap between traces, distance to valve (g), and coil radius determine EM force for a given coil current.
- Through wafer etch radius (r_i), valve boss overlap (olap) and opening height (b) determine open valve flow rate.
- Pressure force determined by gage pressure and valve are (Pi x through wafer etch radius squared).

b

Single sided coil – valve closed



Double sided coil – valve open