RF-MEMS metal contact capacitive switches

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Target specifications RF-MEMS switch
for communications switching matrix

Frequency range	1-30 GHz
Insertion loss	< 0.4 dB
Isolation	> 50 dB
Return loss	> 20 dB
Actuation voltage	< 50 V
Switching time	"small"
Power consumption	"minimal"
Operating ambient	-25 to +75 °C
Life time	10^6 cycles

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Configuration & Choice of switching device meeting specs

Circuit configuration:
series or *shunt*

- compatible with ES actuation
- switching of DC signals not required
- allows switch configuration
- expected better reliability
- basic technology available (with Ta_2O_5)

Switching contacts:
resistive or *capacitive*

- low power consumption
- "easy" and well-known technology
- spec allows up to 50 V_{dc} bias

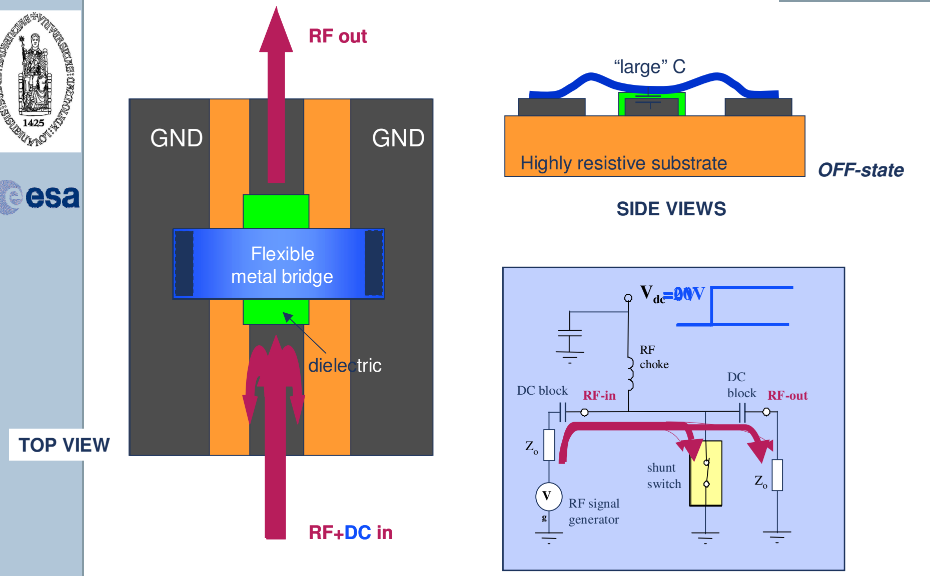
Actuation mechanism:
Electrostatic (ES), electromagnetic, electrodynamic, electrothermal, ….

Driving configuration:
switch or *relay*

- simple structure
- compact (more robust)
- pin compatibility with FET and PIN diodes

Position of the armature (with respect to TL):
inline or *broadside*

Shunt capacitive RF-MEMS switch implemented on a CPW line



It is the capacitance ratio that counts:

$$IL<IL_{spec} \text{ AND } I>I_{spec}$$

in the frequency band $<\omega_l, \omega_u>$ requires that:

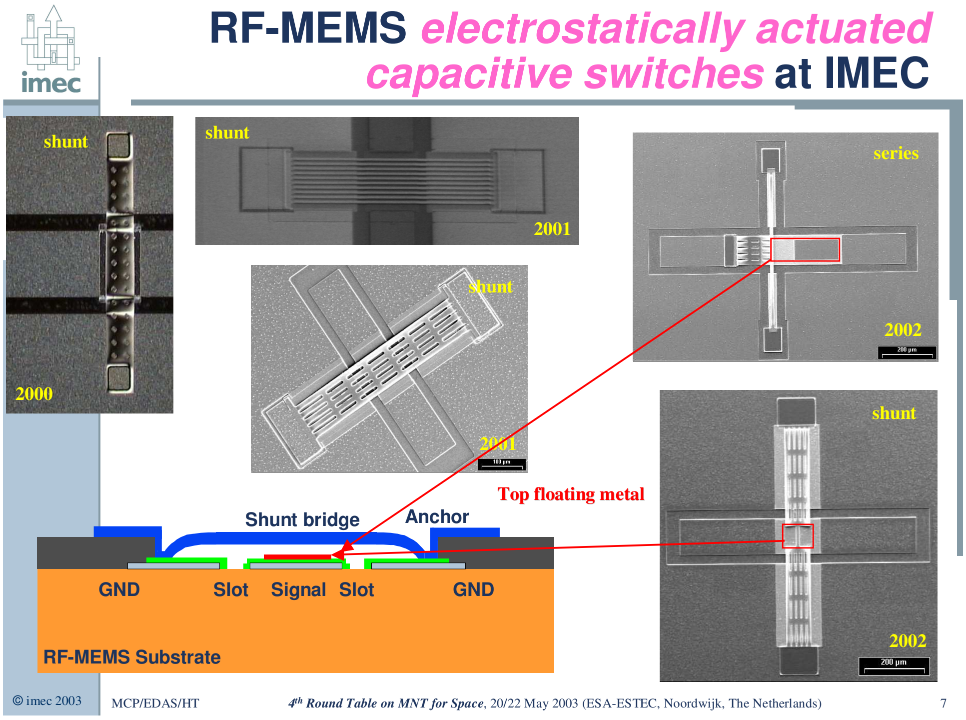
$$r \equiv \frac{C_{down}}{C_{up}} > \frac{\omega_u}{\omega_l}\sqrt{\frac{10^{0.1I_{spec}}-1}{10^{0.1IL_{spec}}-1}}$$

Switch modeled as lumped capacitor
Applies for series and shunt switches

Capacitance ratio determined by process (not geometry):

$$r \equiv \frac{C_{down}}{C_{up}} = \frac{\varepsilon_r d_o}{d_\varepsilon}$$

Conventional capacitive switch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RF-MEMS electrostatically actuated capacitive switches at IMEC
shunt
2000
shunt
2001
shunt
2001
series
2002
shunt
2002
Top floating metal
Shunt bridge
Anchor
GND
Slot
Signal
Slot
GND
RF-MEMS Substrate
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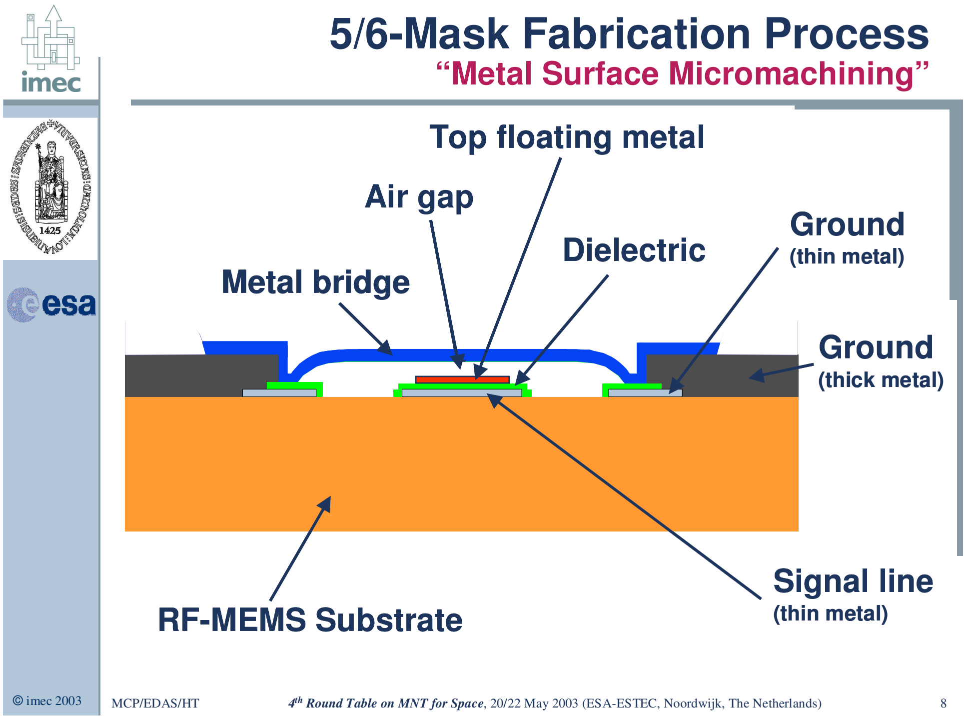
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5/6-Mask Fabrication Process
"Metal Surface Micromachining"
Top floating metal
Air gap
Dielectric
Ground
(thin metal)
Metal bridge
Ground
(thick metal)
Signal line
(thin metal)
RF-MEMS Substrate
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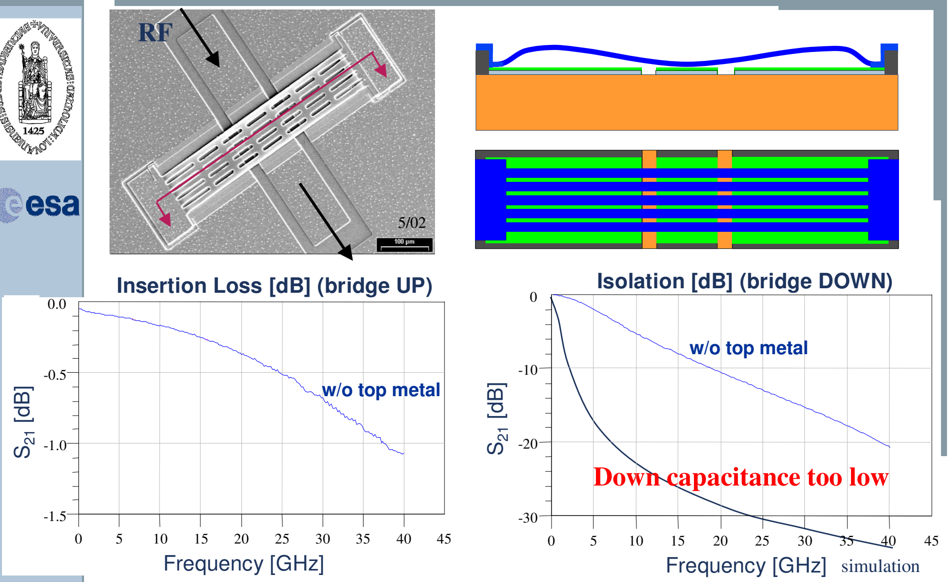
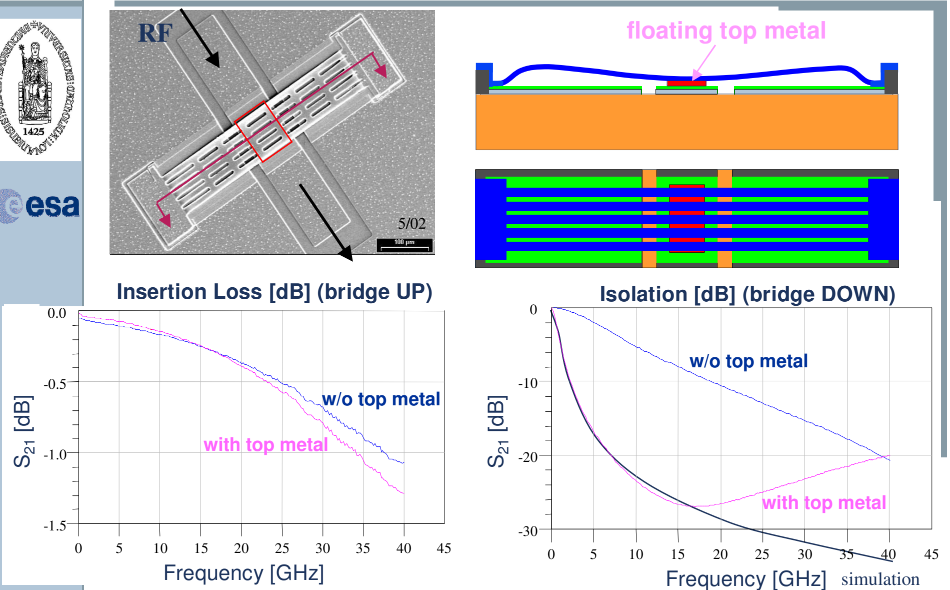
ES actuated capacitive shunt switch:

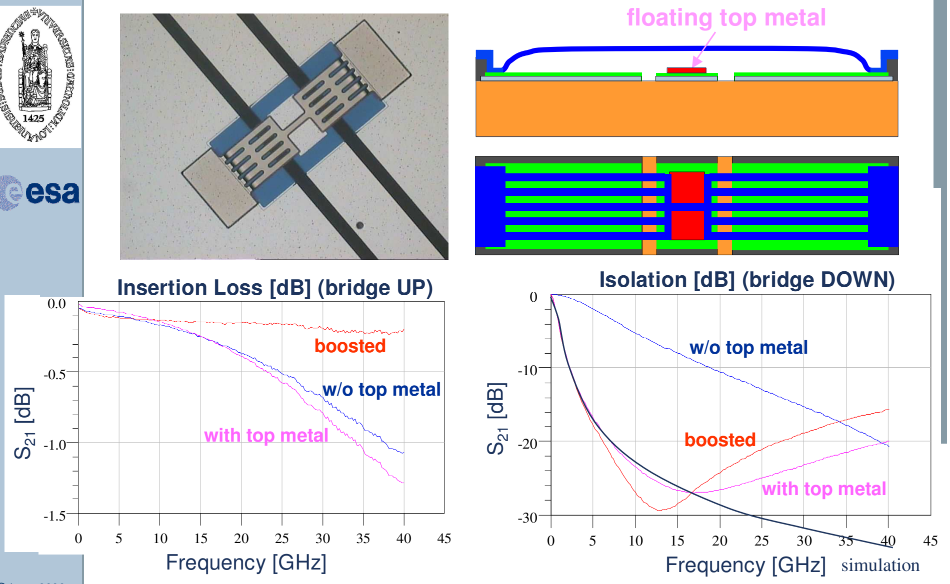


ES actuated capacitive shunt switch:

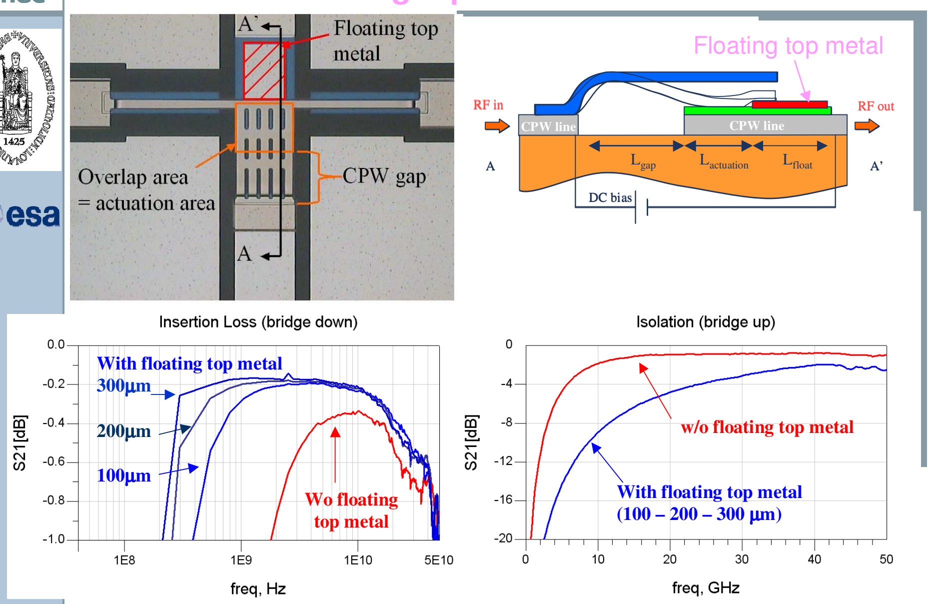
Introduction floating top metal



ES actuated capacitive shunt switch:
Introduction floating top metal → "boosted" switch



ES actuated capacitive series switch:
Introduction floating top metal → "boosted" switch



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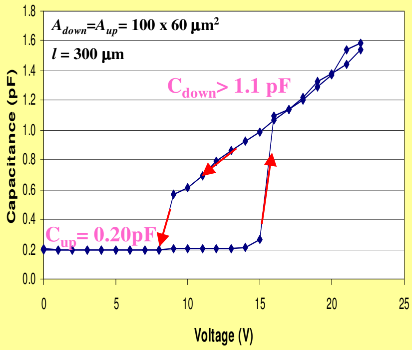
C-V measurements shunt switch

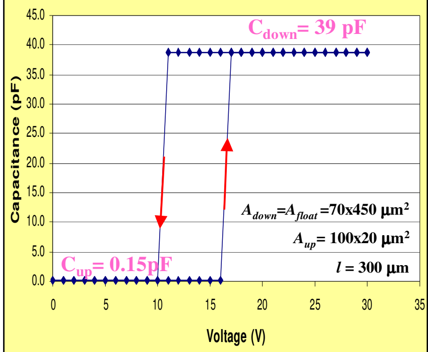
The floating metal makes the difference

w/o top floating metal



- Measured C_{down}<< Predicted C_{down}
- C_{down} increases with increasing bias

with top floating metal



- Measured C_{down}= Predicted C_{down}
- C_{down} independent of bias (>Vpull-in)

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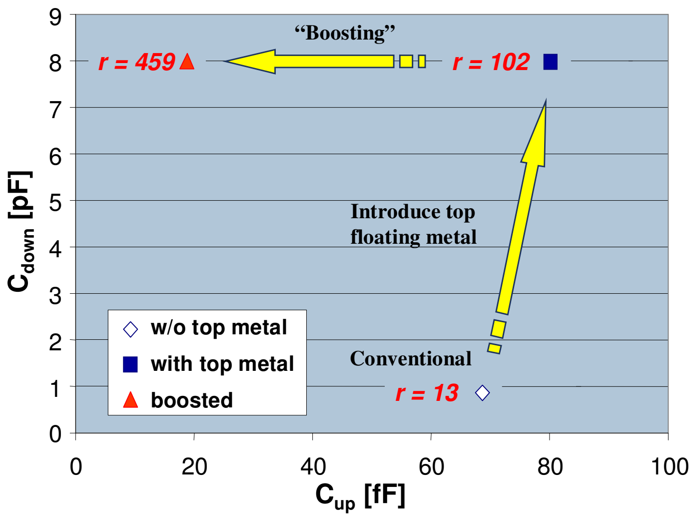
The road to a high $r = C_{down}/C_{up}$ ratio



Conclusions (1): The trick of the *top floating metal*

- Down capacitance C_{down} is <u>predictable</u> and is accurately defined by the area of the top floating metal:

$$C_{down} = \frac{\varepsilon_r A_{float}}{d_\varepsilon}$$

- Area in the down state A_{down} can be chosen "independent" from the area in the up state A_{up} and from the actuation area A_{act}:

$$A_{down} = A_{float} \neq A_{up} \approx A_{act}$$

- Area difference in up and down state can be used to amplify the capacitance area r (boosted concept):

$$r \equiv \frac{C_{down}}{C_{up}} = \frac{\varepsilon_r d_o}{d_\varepsilon} \bullet \frac{A_{float}}{A_{up}}$$

ratio for conventional capacitive switch

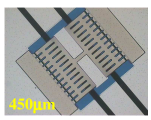
"BOOSTING Factor β"

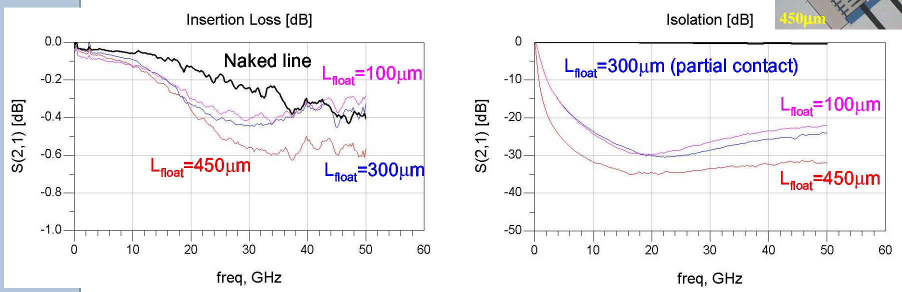
Broadband switching (1-30 GHz)

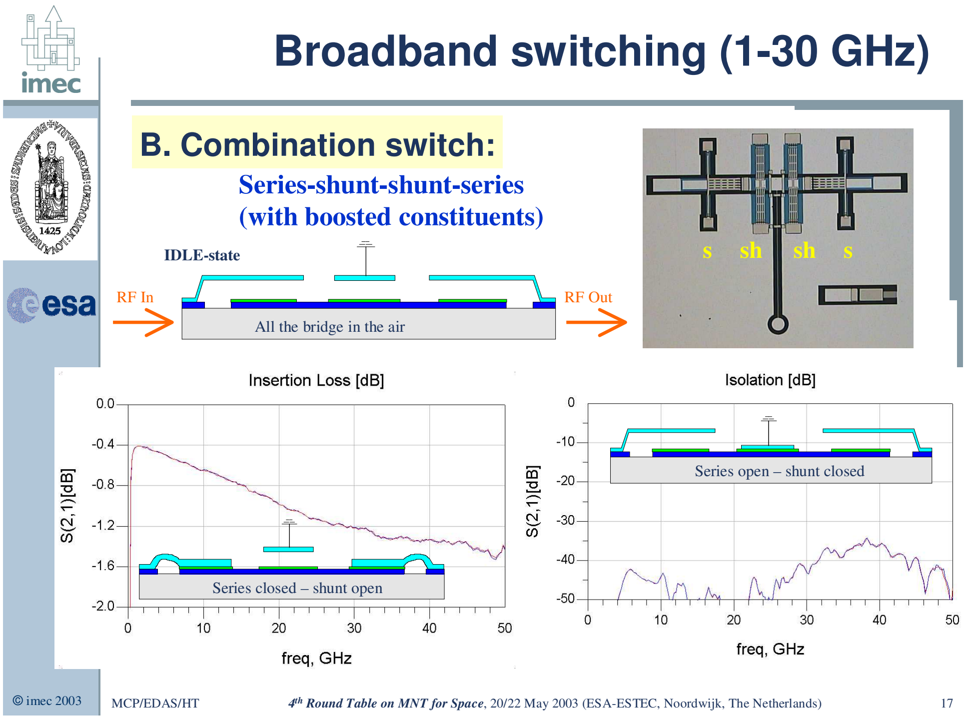
A. Single switch:

- IL<0.4dB and I>50dB over 1-30 GHz requires down/up capacitance ratio ***r*** of: ***r*=C$_{down}$/C$_{up}$ > 30,000** **("impossible" for conventional technology)**
- For a switch technology with ε_r=25, d_o=2.5µm, d_ε=0.2µm, the capacitance ratio is ***r*** **≈ 300** Ł **boosted design** requires a boosting factor **β >100** (*e.g.* if A_{up}= 20x20µm, then A_{float}=4x10^{4}µm^2, or for W_{float} = 70µm, **L_{float} > 0.6mm**)

⇒ **Is feasible**



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Broadband switching (1-30 GHz)
B. Combination switch:
Series-shunt-shunt-series
(with boosted constituents)
IDLE-state
RF In
All the bridge in the air
RF Out
s sh sh s
Insertion Loss [dB]
S(2,1)[dB]
Series closed – shunt open
freq, GHz
Isolation [dB]
Series open – shunt closed
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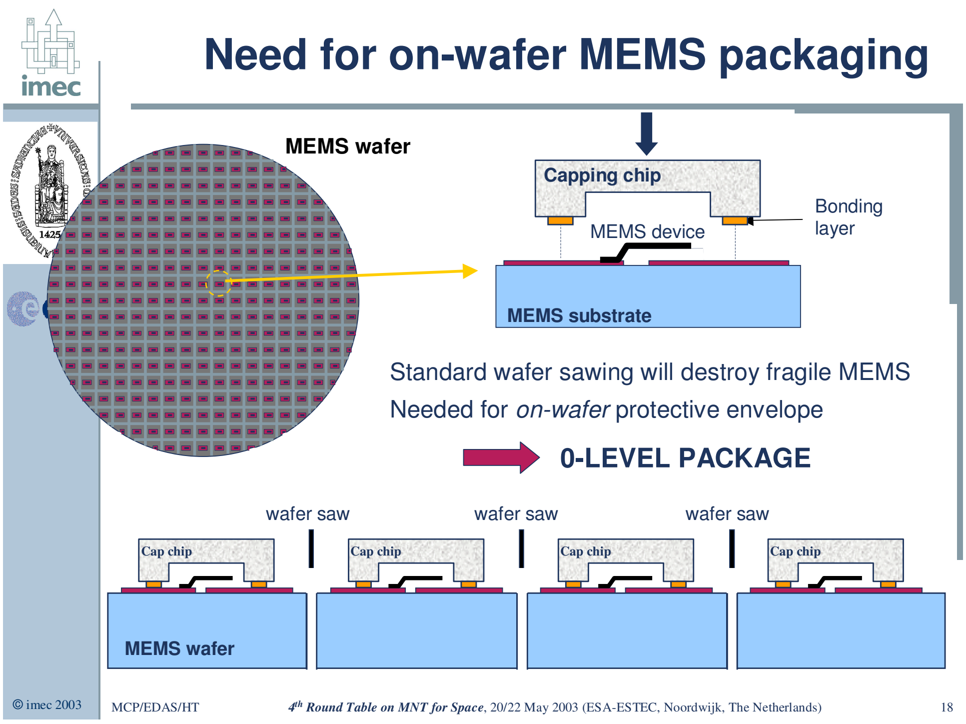
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Need for on-wafer MEMS packaging
MEMS wafer
Capping chip
Bonding layer
MEMS device
MEMS substrate
Standard wafer sawing will destroy fragile MEMS
Needed for on-wafer protective envelope
0-LEVEL PACKAGE
wafer saw
wafer saw
wafer saw
Cap chip
Cap chip
Cap chip
Cap chip
MEMS wafer
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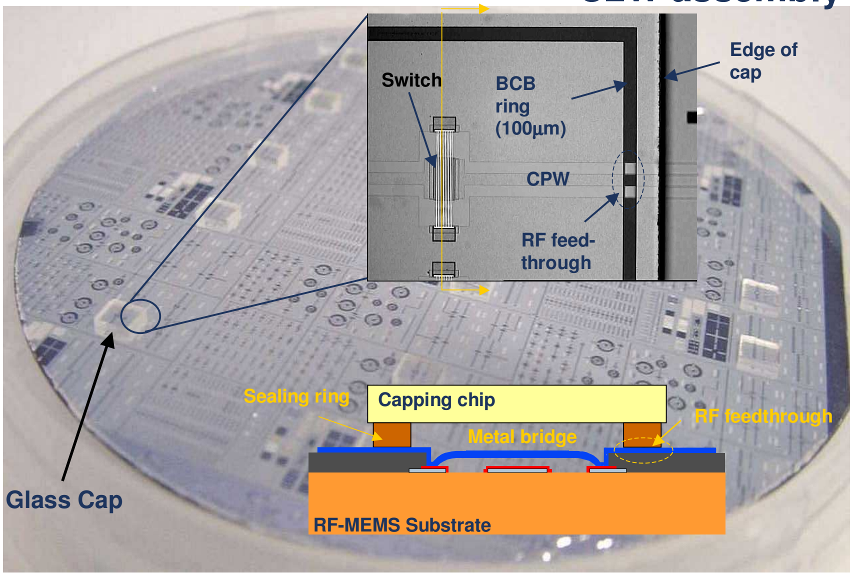
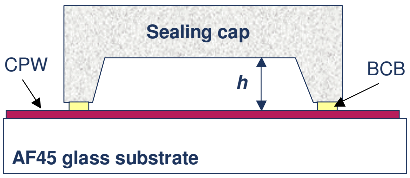
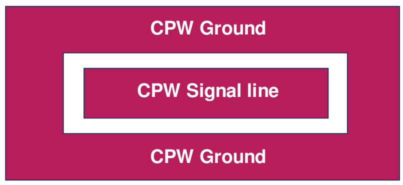
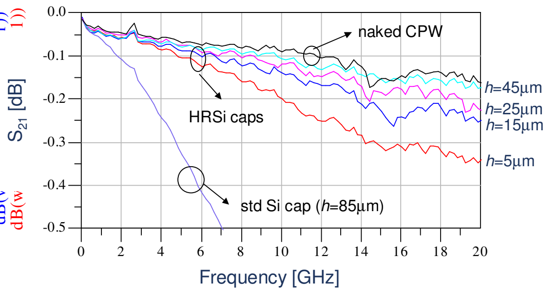
0-level packaged RF-MEMS switches
C2W assembly



Influence of the cap material and cavity height (planar feedthrough)







CPW:
- (25/100/25µm
- Cu 3µm thick
- 2.3 mm long)

AF45 substrate

Cap material:
- standard Si (1-10Ωcm)
- HRSi (>4000Ωcm)

BCB bond (5µm thick)

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Conclusions(2)

- **The implementation of the top floating metal is an easy and viable way to build capacitive switches with predictive RF (and C-V) characteristics.**
- **The boosted capacitive switch approaches the behaviour of the resistive relay, while retaining the advantageous features that are characteristic for a switch configuration (compact, simple, “two-terminal device”).**
- **The specifications IL<0.4dB and I>50dB requires a capacitance ratio better than 30,000; this seems feasible for a single switch, but the ultimate limitation of satisfying the spec is the parasitic resistance and inductance in series with the switch capacitance.**
- **Combination switches improve the RF specifications compared to a single switch design, but this goes at the expense of a higher complexity, increased size (implying higher resistive losses).**
- **The influence of the 0-level package on the RF characteristics can be kept negligibly small.**
- **Critical issues remaining to be solved are:**
  - packaging (hermeticity, controllability, cost)
  - reliability (stiction, life cycles, choice of materials)

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