Development of high gain / MTF CMOS electron detectors for transmission electron microscopes

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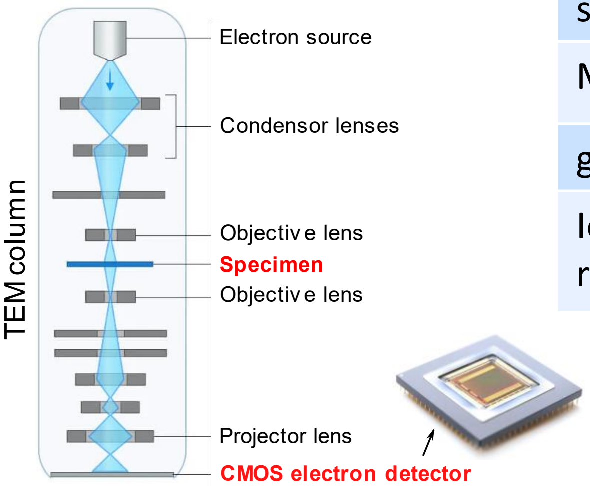
Direct electron detection for TEM

Transmission Electron Microscope (TEM)



	Indirect detection	Direct detection
scintillator	yes	No
MTF	poor	High
gain	average	average
Ionizing radiation	poor	Strong (>100 Mrad)

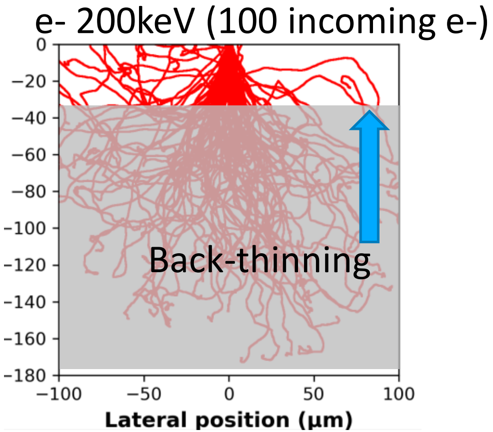
$$gain = \frac{integrated\ electrons}{incoming\ electrons}$$

Remarks:

- MTF ➔ detector sharpness
- Gain ➔ detector sensitivity

Direct electron detection for TEM

- Nowadays, strategies developed by camera providers for improving the MTF:



- Back-thinning the substrate :
  - ➔ ⊕ reduction of lateral diffusion of electrons
  - ➔ ⊖ strong decrease in sensitivity (gain)
  - ➔ ⊖ demonstrated at 300keV [1]

[1] McMullan, Experimental observation of the improvement in MTF from backthinning a CMOS direct electron detector, Ultramicroscopy, 2009

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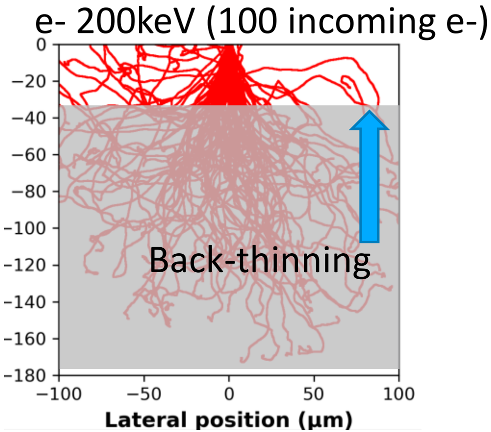

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- + Large pixel [2]:
  - ➔ ⊕ less e- in adjacent pixels
  - ➔ ⊖ small pixel number

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[2] Sannino, A rad-hard, 60µm pixel sensor optimized for the direct detection of electrons, IISW, 2021

Direct electron detection for TEM

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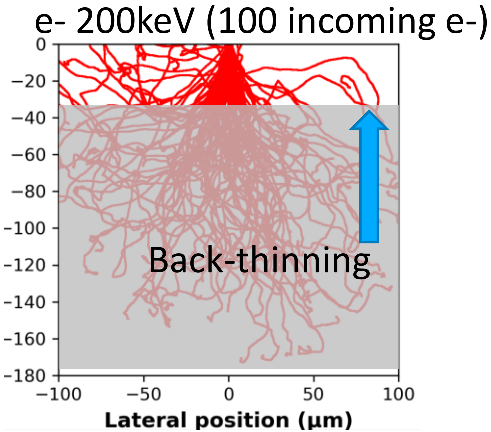

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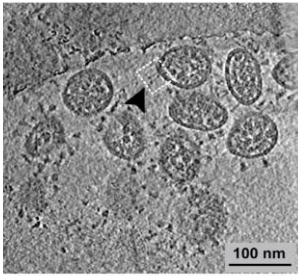
- Needs for new advanced TEM techniques (Cryo TEM, …):
  - Reduce electron dose at 200keV ➔ improve the GAIN
  - Keep good MTF performances at 200keV



Cryo-TEM observation of Covid 19 [3]

[1] McMullan, Experimental observation of the improvement in MTF from backthinning …, Ultramicroscopy, 2009
[2] Sannino, A rad-hard, 60µm pixel sensor optimized for the direct detection of electrons, IISW, 2021
[3] Yao 2020, Molecular Architecture of the SARS-CoV-2 Virus

Goal of this study

- Propose new silicon substrates (thickness / doping) for detectors compatible with 200 keV electron beam:
  - Improving the detector gain
  - Keep / improve MTF performance

$$gain = \frac{integrated\ electrons}{incoming\ electrons}$$

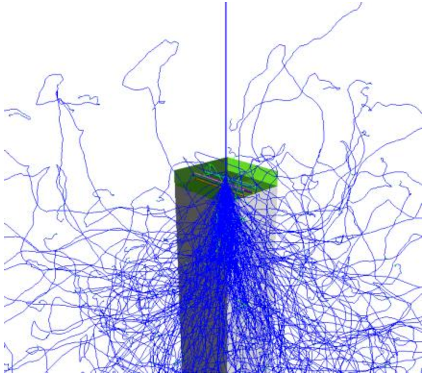
Detector	Pixel type	substrate	Gain	MTF at half Nyquist
State of the art (Gatan K3, FEI Falcon)	3T – hardened by design	$> 10^{15}$B/cm^3 Back thinned < 15µm	< 40	0,2 – 0,3
Our goal	3T – hardened by design	$< 10^{15}$B/cm^3 Thicker substrate	>200	0,2 – 0,3

- Tool: TCAD simulations, methodology demonstrated with in-situ measurements [3]

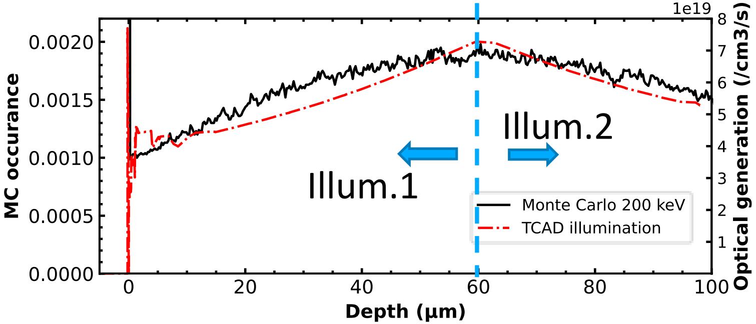
[3] Marcelot, A New TCAD Simulation Method for Direct CMOS Electron Detectors Optimization, ultramicroscopy, 2022

TCAD simulation settings

- TCAD tools do not provide options for particle simulations
- **The electron simulation is simulated by means of 2 optical illuminations**

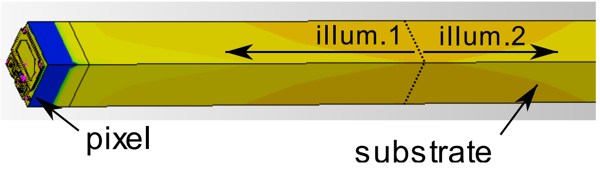


Casino: Monte Carlo
e- distribution



Monte Carlo profile

Synopsys optical generation
$\lambda = 960nm$



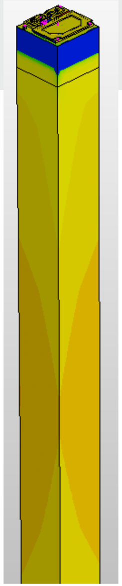
TCAD simulation settings

- **Gain** simulation:
  - 3D simulation
  - $gain = \frac{N_e(pix)}{N_e(illum)\times Ratio(\frac{e_1}{e_2})}$

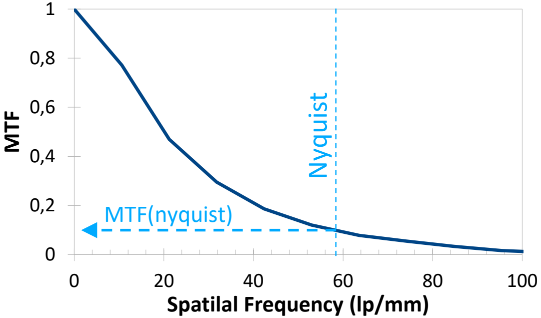
Integrated e-

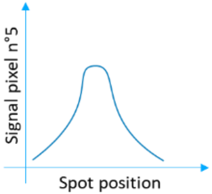
Optically generated e-

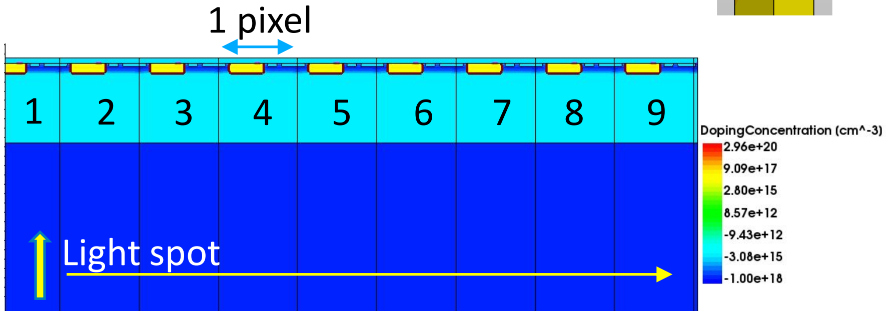
Ratio of primary / secondary e- (Monte Carlo output)



- **MTF** simulation:
  - 2D simulation of 9 pixels
  - simulation of LSF
  - MTF = FT (LSF)

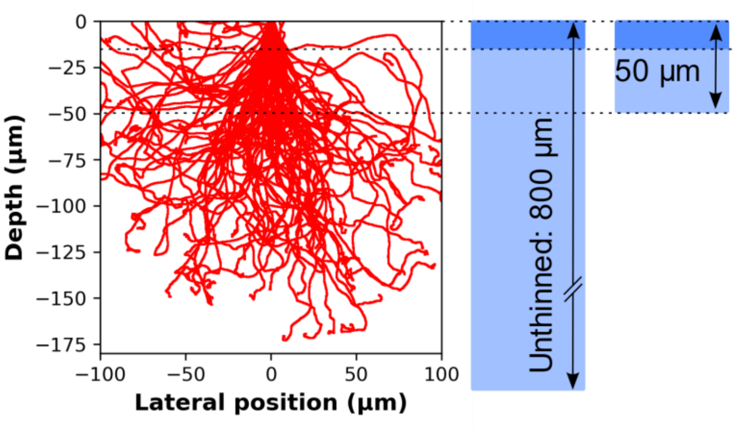






TCAD simulation settings

- **Device:** 3T pixel, pitch 8.5µm, 1.8V bias
- **Comparison** with a state of the art - like detector, simulated on a 10µm substrate doped at 10^{17}B/cm^3 [4]
- **Substrates**:
  - Epi doped at 10^{15}B/cm^3 -10^{12}B/cm^3, thickness 5, 7, 15 and 30µm
  - Unthinned substrates
  - Back-thinned substrates (to 50µm)



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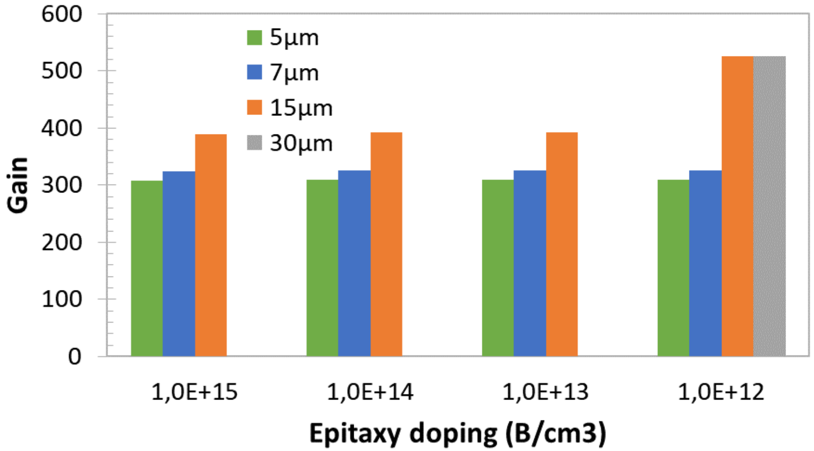
[4] Krieger, Fast, radiation hard, direct detection CMOS imagers for high resolution transmission electron microscopy, IEEE NSSCR, 2011

Results for un-thinned substrates

- Gain simulation for a 200 keV e- beam



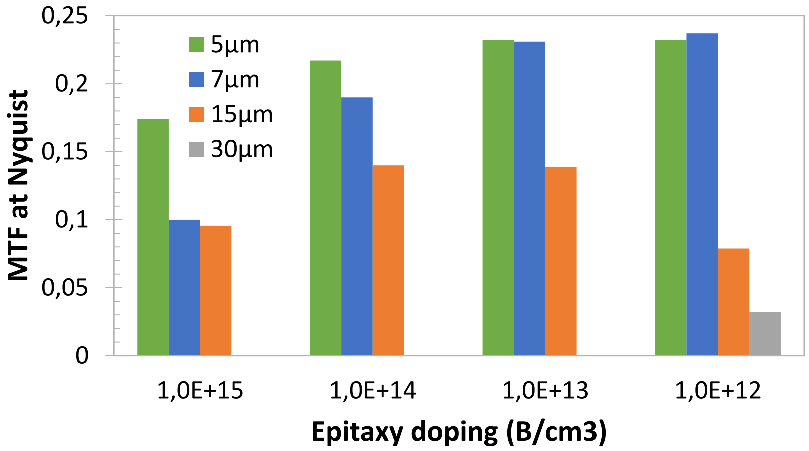
TCAD	Beam energy (keV)	Epi doping (B/cm^3)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art	200	10^{17}	10	125	0,09
	300		10	27	0,14

- The gain is x2,5 with unthinned substrate compared to the state of the art
  - Much larger collection volume

- Reducing the epitaxy doping does not increase the gain : e- mainly generated deeply, far from the epitaxy region
- The gain increases with the epitaxy thickness, because e- are easily recombined in the highly doped substrate

Results for un-thinned substrates

- MTF simulation for a 200 keV e- beam



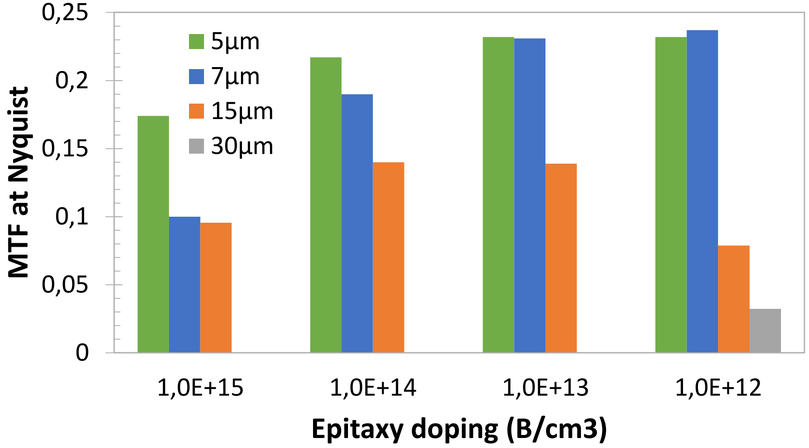
TCAD	Beam energy (keV)	Epi doping (B/cm^3)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art	200	10^{17}	10	125	0,09
	300		10	27	0,14

- The MTF can be 2x higher compared to the state of the art

- Reducing the epitaxy doping increases the MTF for epi <7µm: a larger depleted volume reduces the collection in adjacent pixels
- Increasing the epitaxy thickness >7µm does not help because of the longest e- lifetime in epi layer ➔ more collection in adjacent pixels

Results for un-thinned substrates

- MTF simulation for a 200 keV e- beam



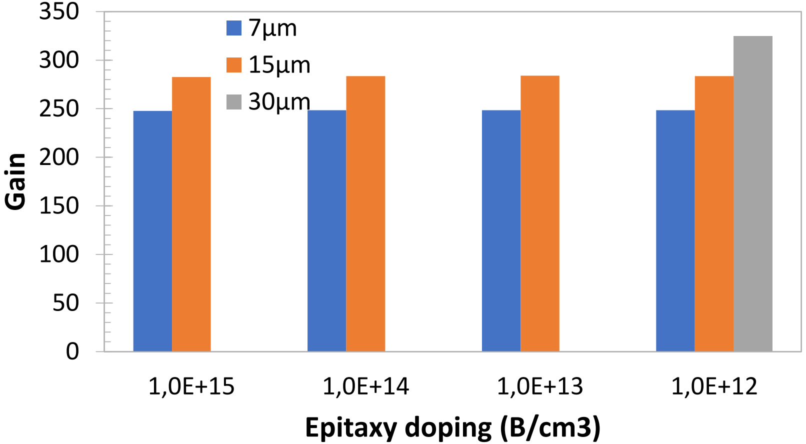
TCAD	Beam energy (keV)	Epi doping (B/cm³)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art	200	10^{17}	10	125	0,09
	300		10	27	0,14
unthinned	200	10^{13}	7	325	0,23

- The MTF can be 2x higher compared to the state of the art
- Best candidate: epi 10^{13}B/cm³, 7µm

- Reducing the epitaxy doping increases the MTF for epi <7µm: a larger depleted volume reduces the collection in adjacent pixels
- Increasing the epitaxy thickness >7µm does not help because of the longest e- lifetime in epi layer ➔ more collection in adjacent pixels

Results for 50µm back thinned substrates

- Gain simulation for a 200 keV e- beam



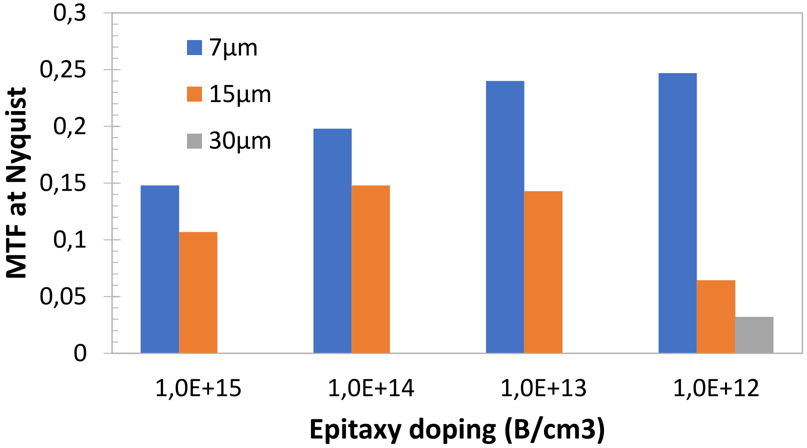
TCAD	Beam energy (keV)	Epi doping (B/cm³)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art	200	10^{17}	10	125	0,09
	300		10	27	0,14
unthinned	200	10^{13}	7	325	0,23

- The gain is x2 with 50µm thinned substrate compared to the state of the art

- The lower collection volume induces less generated electrons and less signal… The conclusion is even worse for thinner substrates.
- Same observations related to epitaxy doping and thicknesses, compared to un-thinned substrates.

Results for 50µm back thinned substrates

- MTF simulation for a 200 keV e- beam



TCAD	Beam energy (keV)	Epi doping (B/cm³)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art	200	10^{17}	10	125	0,09
	300		10	27	0,14
unthinned	200	10^{13}	7	325	0,23
50µ BS	200	10^{12}	7	248	0,25

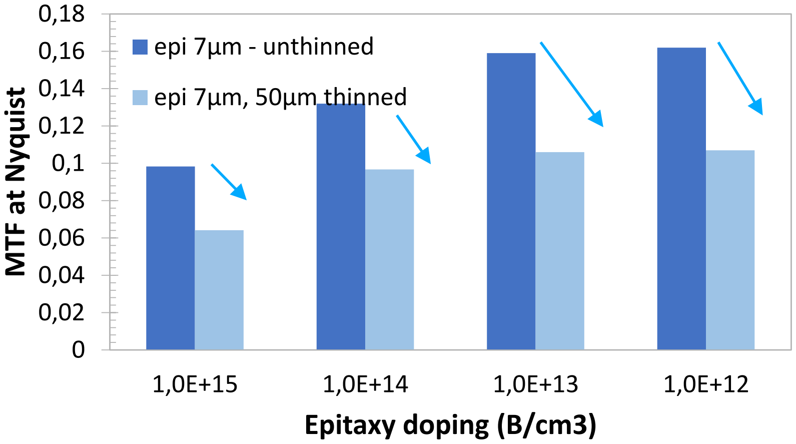
- The MTF is not higher compared to un-thinned substrates ➔ in opposition with [1]

- Compared to 300keV, 200keV e- are generated closer to the surface, inducing more e- near the epitaxy layer. Back-thinning does not help as less e- can be recombined.
- Same observations related to epitaxy doping and thicknesses, compared to un-thinned substrates.

[1] McMullan, Experimental observation of the improvement in MTF from backthinning a CMOS direct electron detector, Ultramicroscopy, 2009

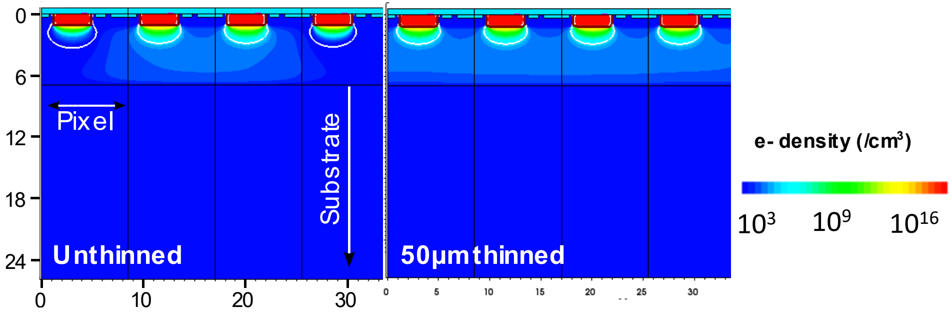
Results for 50µm back thinned substrates

- MTF may become even worse with 50µm back-thinned substrate with lower beam energy
- MTF simulation for a 150 keV e- beam



TCAD simulation of 4 pixels after integration for 150keV electrons in a 10^{15}B/cm^3, 7µm epitaxy. Beam position: x=17µm.

- e- in un-thinned substrates are mainly recombined in the bulk
- For 50µm substrate, e- are not well recombined due to the lower bulk volume ➔ collection in adjacent pixels ➔ ↘ MTF



Conclusions

- This work demonstrates the possibility to develop new electron detectors with superior gain and MTF performances, based on substrate modifications:

TCAD	Beam energy (keV)	Epi doping (B/cm^3)	Epi thickness (µm)	Gain	MTF at Nyquist
State of the art, back-thinned substrate	200	10^{17}	10	125	0,09
Un-thinned substrate	200	10^{13}	7	325	0,23

- In contrary to previous study, it is shown that a back-thinned substrate (<50µm) does not help in improving the MTF with conventional beam energies (<200keV)
- Perspectives:
  - Perform future measurements on detectors based on low doped epitaxies
  - Study the possibility to use 4T pixels for improved gain conversion (CVF)
  - Develop a direct integration of e$^-$ MC outputs into the TCAD workflow

Thanks for your attention…

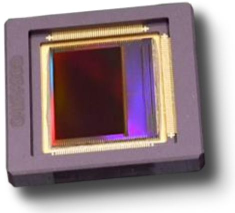
… any questions?

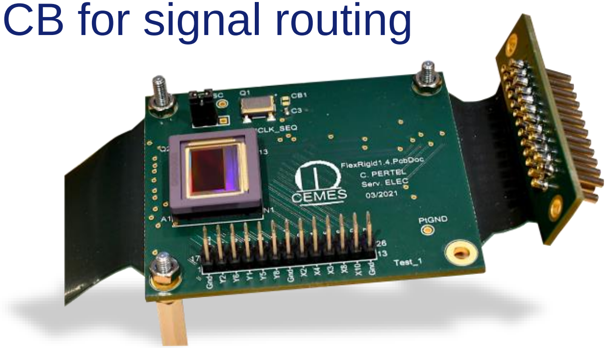
Institut Supérieur de l'Aéronautique et de l'Espace

SUPAERO

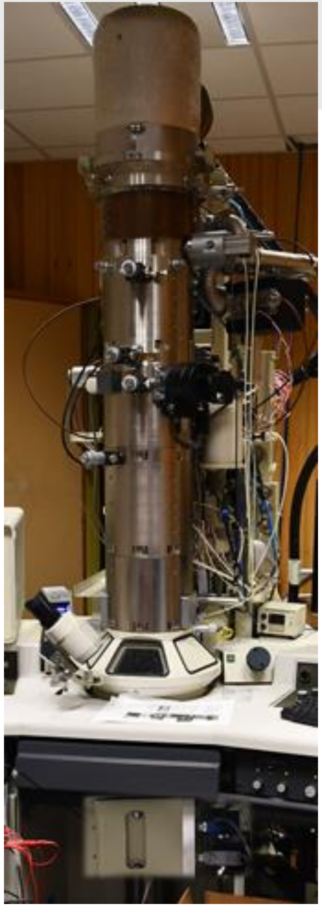
Experimental set-up

- CMOS image sensor : 720 x 1280 pixels
  - 8,5µm pitch, 7µm epi
  - developed in a 180nm technology
  - Radiation hardened at >100 Mrad [1]
- Custom designed PCB for signal routing





- PCB fixed in a Gatan cube – under a Hitachi HF2000 TEM



[1] V. Goiffon, CAMRAD: Development of a Multi-Megagray Radiation Hard CMOS Camera for Dismantling Operations, 2018

Perspectives

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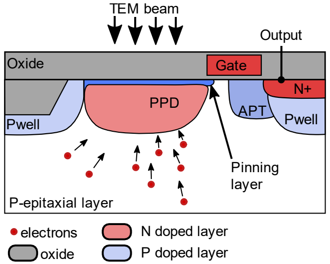

State of the art GAIN → x2,5 → Optimized substrate → x10 → PPD: high CVF