

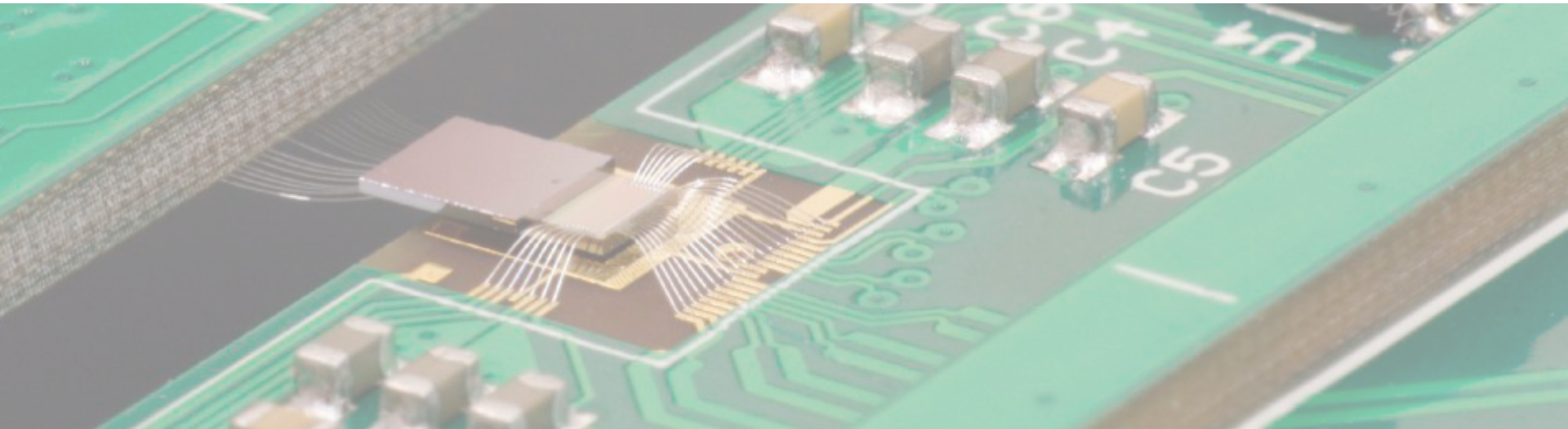


UNIVERSITÉ
DE GENÈVE



HV-CMOS Coupling Simulation*

* Updated on Sept 27th

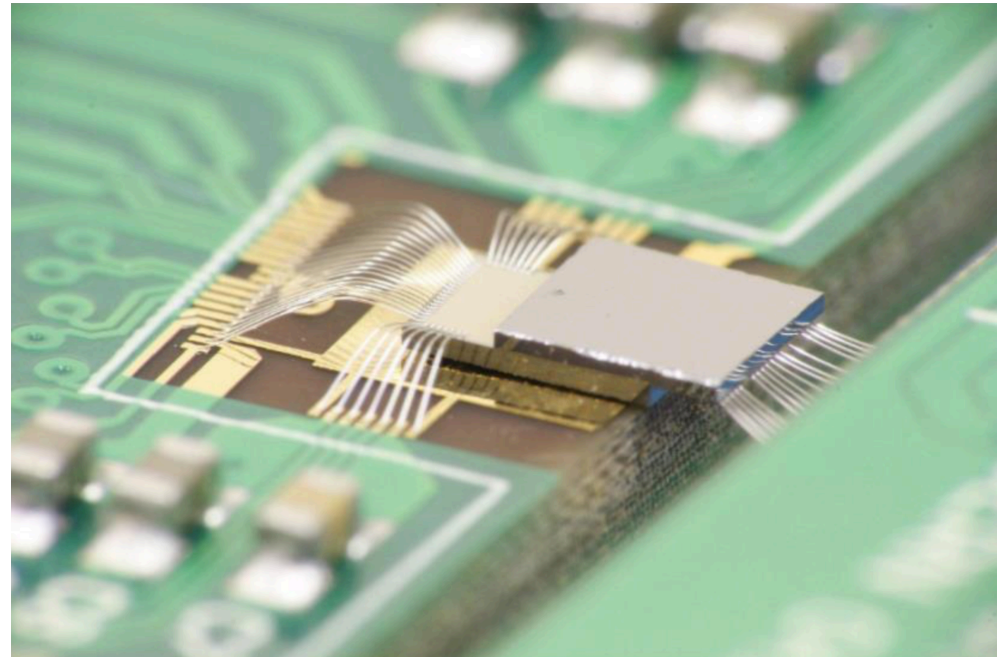


CLICpix + CCPDv3. Szymon Kulis - <http://skulis.web.cern.ch/skulis/clicpix/>

Outline

2

- Introduction to Capacitive Coupling
 - ▣ Detector assembly
- Objective
 - ▣ Find coupling between pixels
 - Maxwell Capacitance Matrix
 - ▣ Simulate existing chips
 - Understand observed performance
 - ▣ Simulate new chips
 - Optimize design
- Simulation
 - ▣ Physics model
 - ▣ COMSOL Multiphysics
 - ▣ Geometry
- Results
 - ▣ and discussion
- Conclusions



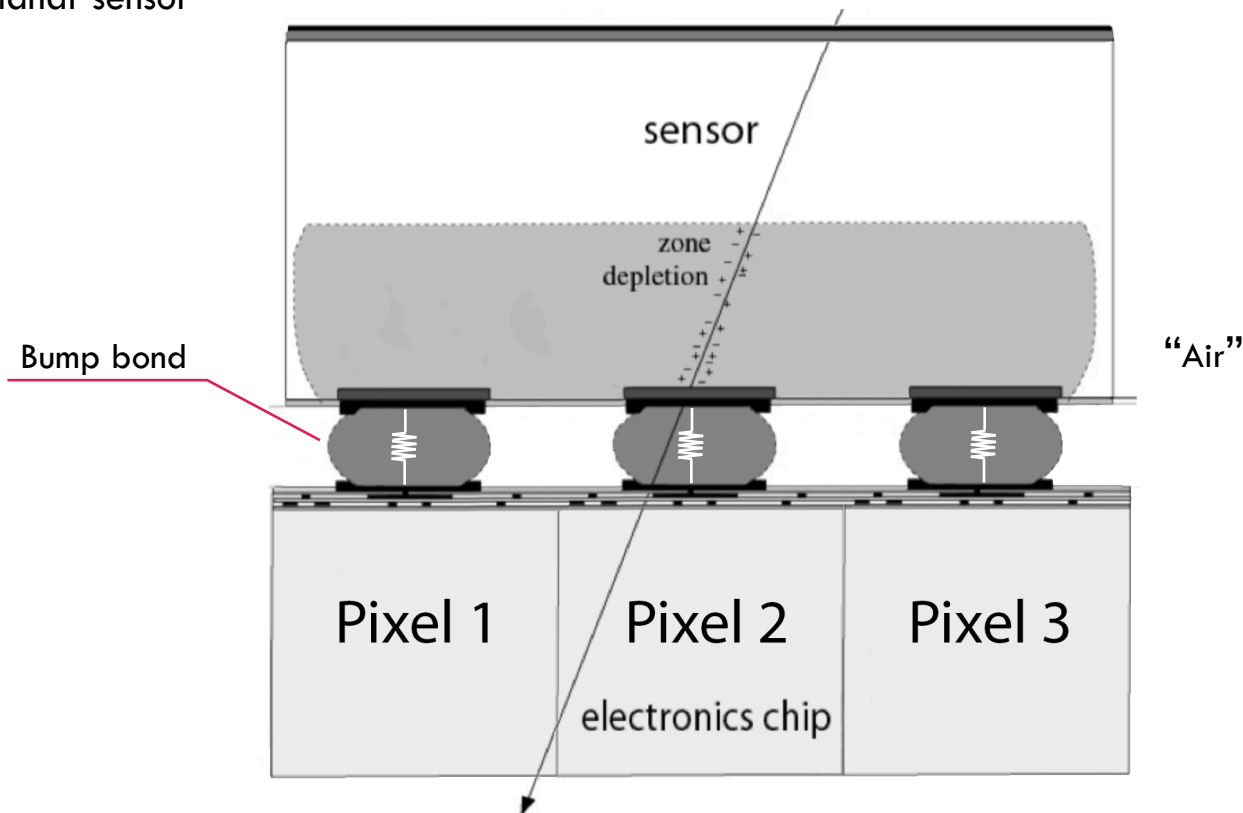
CLICpix Coupled to CCPDv3. Szymon Kulis - <http://skulis.web.cern.ch/skulis/clicpix/>

Detector Assembly

Hybrid detector bump-bonded (DC Coupled)

3

- Signal transmitted from sensor pixel to read-out pixel by a metallic connection (bump bond)
 - ▣ Planar sensor

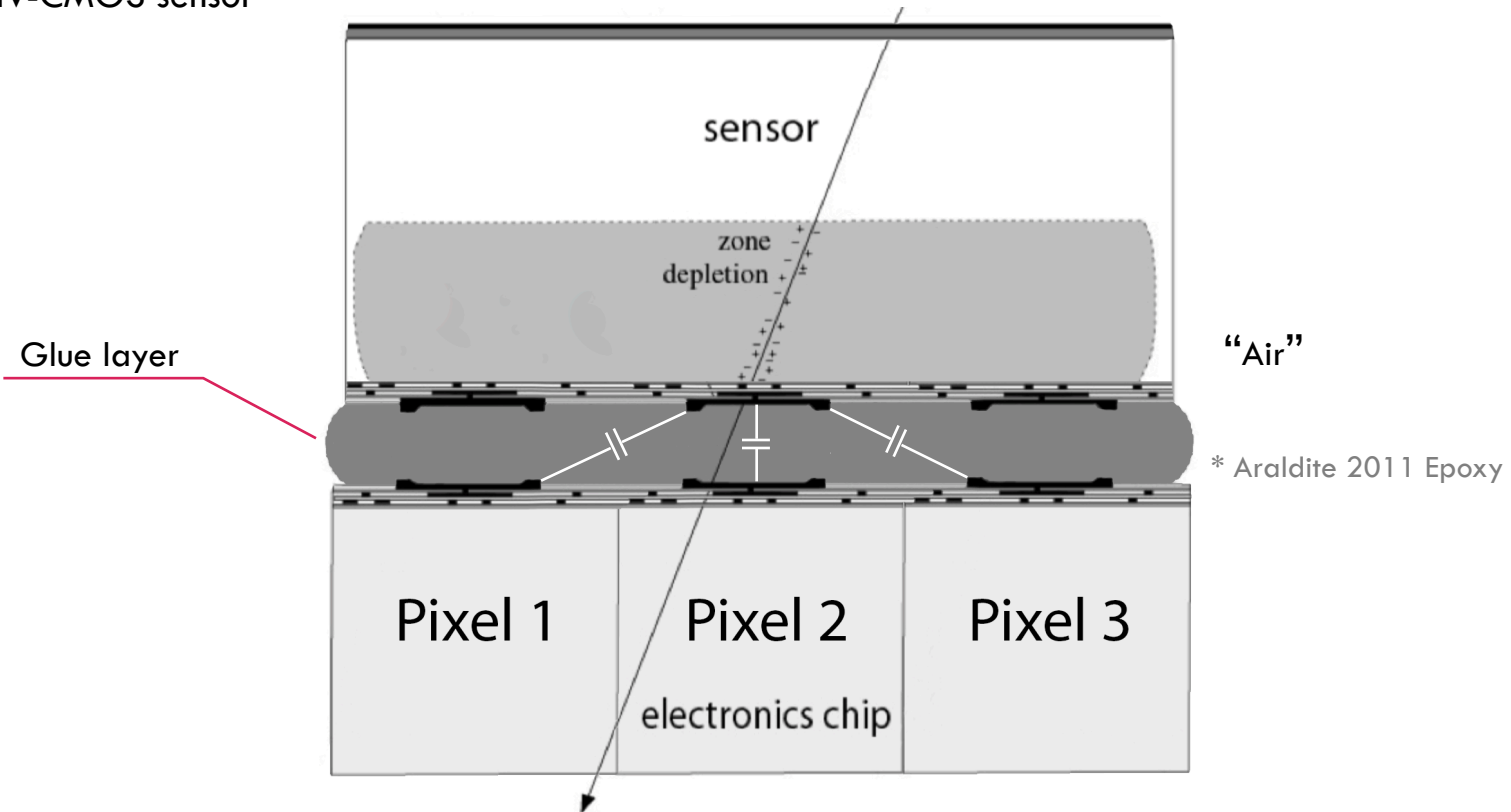


Detector Assembly

Hybrid detector glued (AC Coupled)

4

- Signal capacitively transmitted from sensor pixel to read-out pixel through a dielectric glue layer*
- ▣ HV-CMOS sensor

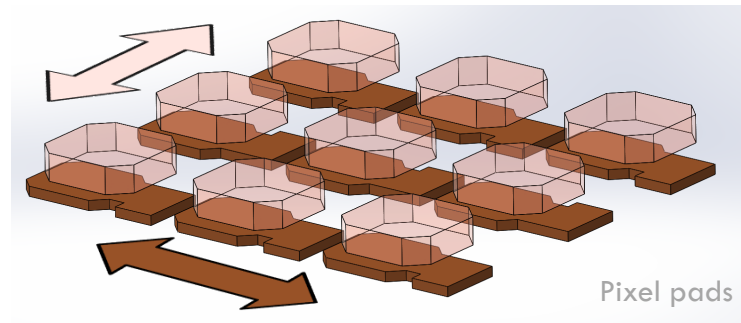


Chips Bonding

Flip-Chip with the Accura 100 machine*

5

- ❑ Heating up to **400C** and force applied by bonding arm up to **100 kg**
- ❑ XY Alignment stage with resolution of **0.015 μm**
- ❑ Post bonding accuracy **< 0.5 μm ****
 - ❑ ** Not straightforward. Special software created to help on chip alignment (*PixelShop*)



*At Geneva University



Chips Assembly

CLICpix + CCPDv3

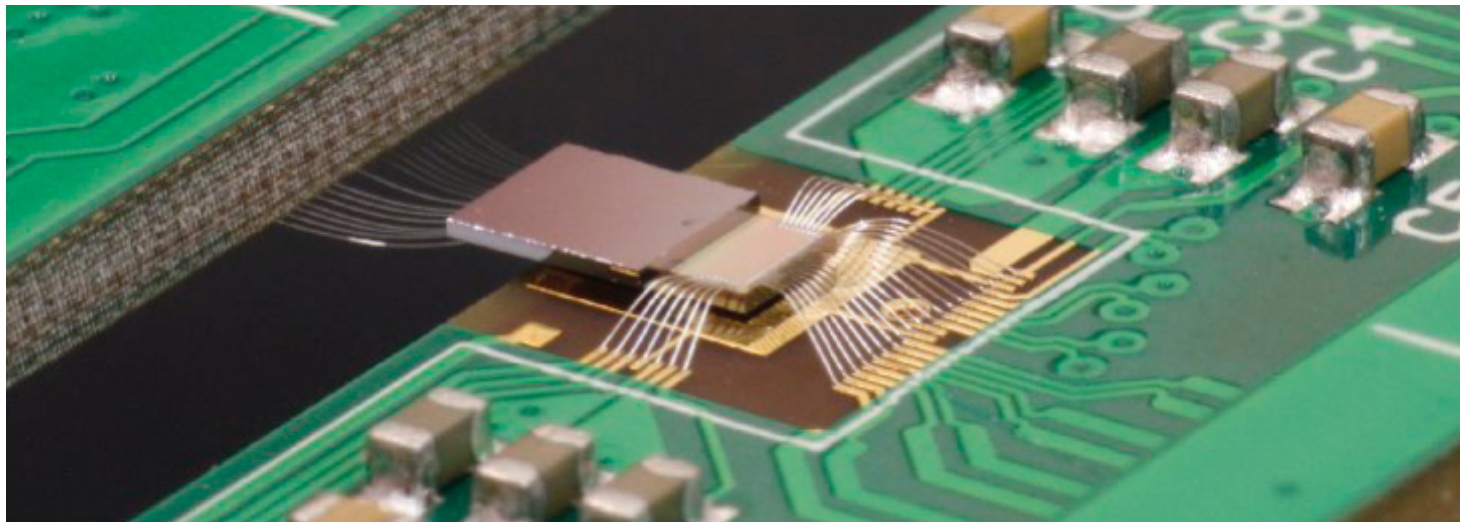
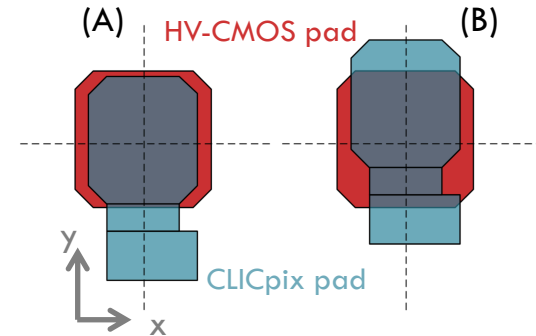
6

□ CLICpix + CCPDv3 assemblies produced

▣ Assemblies studied in Test Beam

- Early measurements: Assemblies with pad alignment (A)
- Later measurements: Assemblies with “ideal alignment” (B) and with offset in x-direction by 1/4 pixel or 1/2 pixel.

▣ Assemblies for cross-section measurements were produced with pad alignment (A).



CLICpix + CCPDv3. Szymon Kulis - <http://skulis.web.cern.ch/skulis/clicpix/>

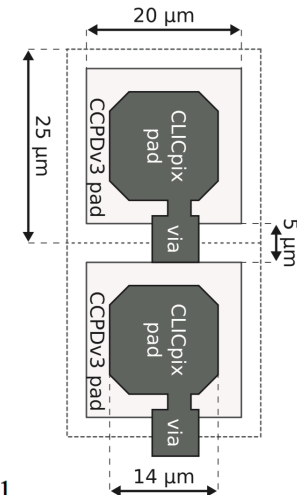
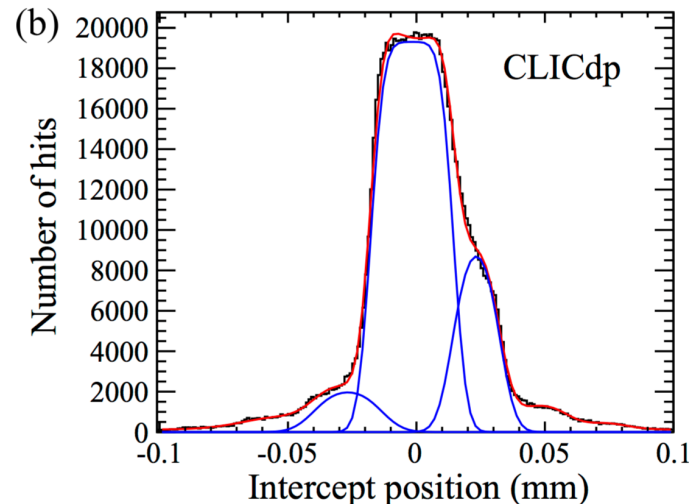
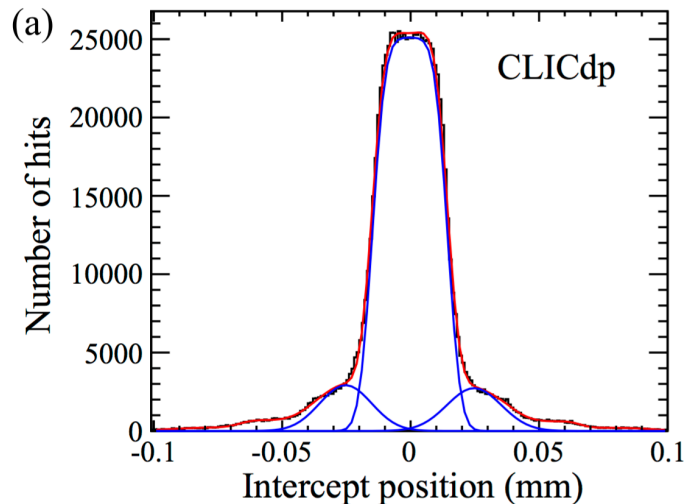
mvicente@cern.ch 31/08/16

Chips (Mis)Alignment?

Asymmetric pixel response in Test Beam data

7

- Pixel response function
 - ▣ Ideal function should be smeared rectangular function with width described by the lateral charge diffusion
- Difference response in row and column directions
 - ▣ Possible misalignment in the Col (a) and/or Row (b) direction



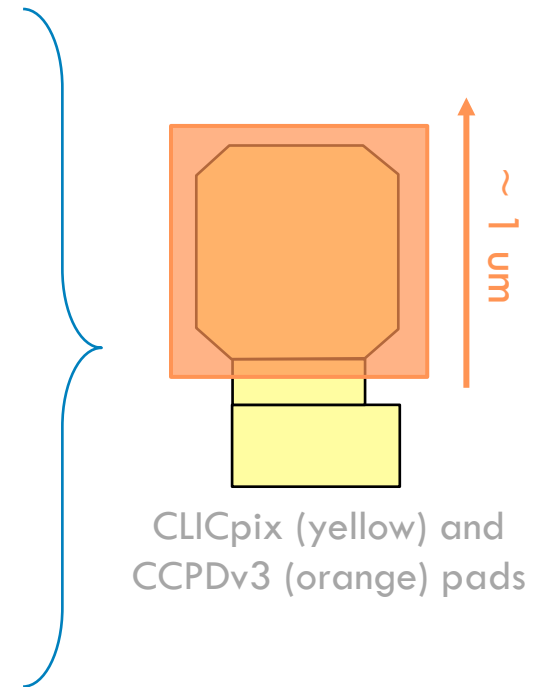
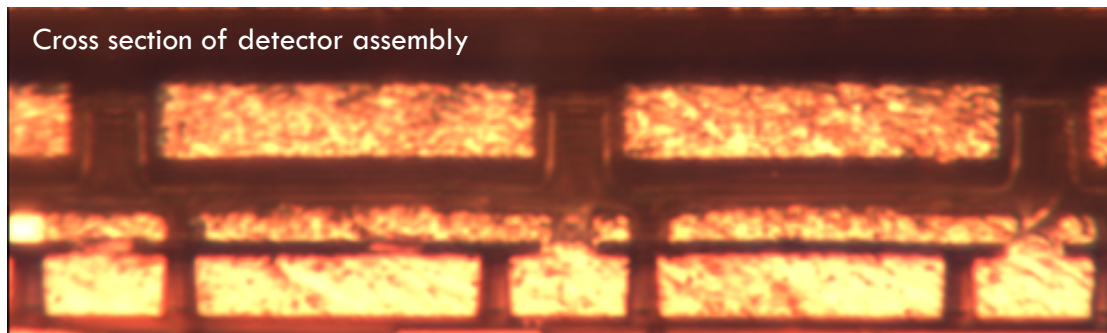
Nucl. Instrum. Meth. A823 (2016) 1

Assembly Measurement

Cross Section after Flip-Chip

8

- Measurement of SET29 sample (CLICpix + CCPDv3) with an optical microscope
 - ▣ Bump pads misaligned (with respect to **A**) by $\sim 1.1\mu\text{m}$ (after bonding process)



SET29 measurement thanks to Florian Pippert

Physics model

9

- Relationship between the charge and electric potential of different terminals
- Purely Geometric (+ material dependency)!!!

- Quantitatively

- Maxwell Coefficients of Capacitance in the backup

$$C_{ij} \equiv -\epsilon_0 \oint_{S_i} \nabla f_j \cdot \mathbf{n}_i dS$$

- Qualitatively

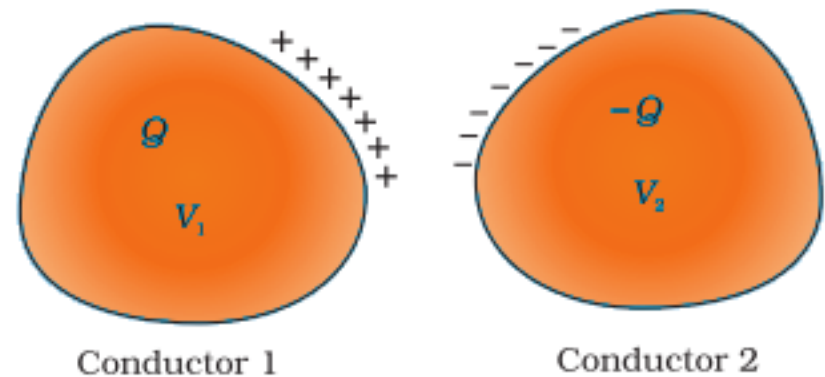
Scott Hughes - Lecture 6: Capacitance – MIT 2005

$$V \equiv \phi_2 - \phi_1 = -\int_1^2 \vec{E} \cdot d\vec{s}$$

Independent of the integration path

Potential difference V must be proportional to the geometry

$$V = \underbrace{(\text{Horribly messy constant depending on geometry})}_{\text{Capacitance}} \times Q$$



- Materials

Capacitance

- Glue + 4 passivation layers (2 from sensor + 2 from the read-out chip)
 - Glue Dielectric Coefficient: 1 Hz = 3.4 | 100 Hz = 3.2 | 1000 Hz = 3.2 | >1000 Hz = <3.2 ? (To be measured)

Physics model

10

- Capacitance between pixels in the CLICpix2 and C3PD chips
- Purely Geometric (+ material dependency)!!!
- Quantitatively

- Maxwell Coefficients of Capacitance in the backup

$$C_{ij} \equiv -\epsilon_0 \oint_{S_i} \nabla f_j \cdot \mathbf{n}_i dS$$

- Qualitatively

Scott Hughes - Lecture 6: Capacitance – MIT 2005

$$V \equiv \phi_2 - \phi_1 = -\int_1^2 \vec{E} \cdot d\vec{s}$$

Independent of the integration path

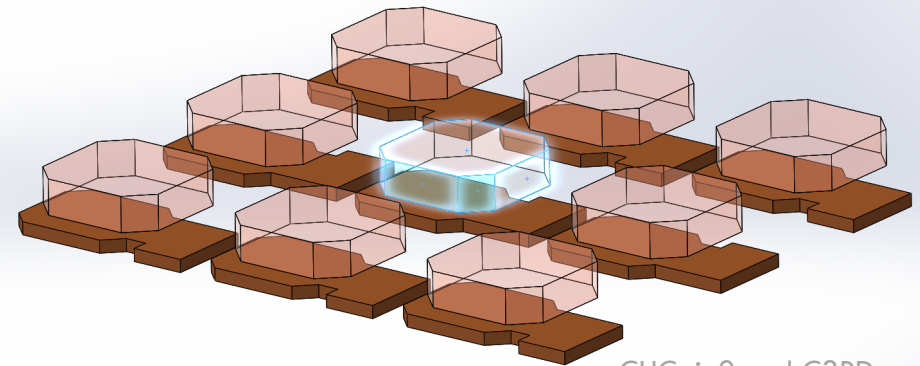
Potential difference V must be proportional to the geometry

$$V = \underbrace{(\text{Horribly messy constant depending on geometry})}_{\text{Capacitance}} \times Q$$

- Materials

Capacitance

- Glue + 4 passivation layers (2 from sensor + 2 from the read-out chip)
 - Glue Dielectric Coefficient: 1 Hz = 3.4 | 100 Hz = 3.2 | 1000 Hz = 3.2 | >1000 Hz = <3.2 ? (To be measured)



CLICpix2 and C3PD pads

Simulation

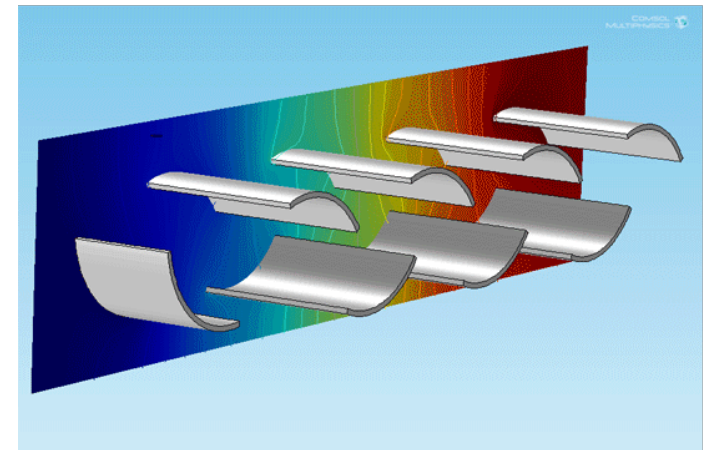
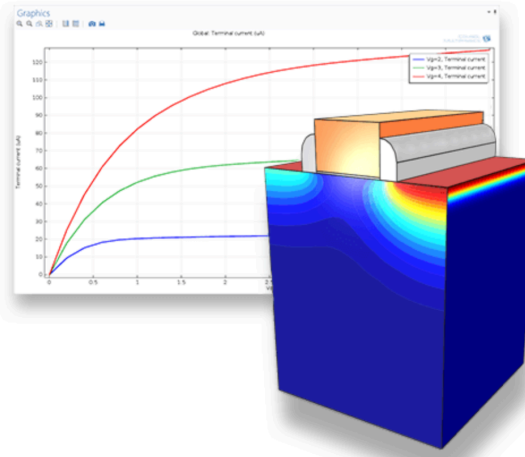
COMSOL Multiphysics®

11

- Key Features @ <https://www.comsol.com/comsol-multiphysics#specs>
 - ▣ **Finite Element Analysis**
 - ▣ Several different templates for general second-order systems of nonlinear partial differential equations
 - Electric currents
 - Heat transfer in solids and fluids
 - ▣ Free tetrahedral meshing
 - ▣ Nonlinear material properties as a function of any physical quantity

Name	Expression	Value	Description
d		3.0000E-6 m	Cold arm bridge width
dw		1.5000E-5 m	Cold arm width
gap		3.0000E-6 m	Gap between arms
wb		1.0000E-5 m	Electrode base width
wv		2.5000E-5 m	Hot arm length difference
L		240[um]	Actuator length
L1	L-wb	2.3000E-4 m	Hot arm A length
L2	L-wb-wv	2.0500E-4 m	Hot arm B length
L3	$L-2 \cdot wb-wv-L/40-L/d$	1.5000E-4 m	Cold arm length
L4	L/6	4.0000E-5 m	Cold arm bridge length
DV		4[V]	Voltage

Name: L3
Expression: $L-2 \cdot wb-wv-L/40-L/d$
Description: Cold arm length



Transistor operation where an applied gate voltage turns the device on and then determines the drain saturation current.

Simulation

Fully Integrated Software Suite

12

Model 1 (mod1)

- > Definitions
- > Geometry 1
- Material 1
 - > Silicon (mat1)
 - > Semiconductor (semi)
 - > Heat Transfer in Solids (ht)
- Mesh 1
 - Size
 - > Free Triangular 1
- Study 1
 - Parametric Sweep
 - Step 1: Stationary
 - > Solver Configurations
 - > Job Configurations
- Results
 - > Data Sets
 - Derived Values
 - Tables
 - > IV Curve
 - > Electron Concentration (semi) 1
 - > Hole Concentration (semi) 1

All modeling steps are available from a single unified environment. The model tree (shown on the left) provides quick and easy access to all the settings:

Geometry setup / CAD /ECAD Import

User defined and built in material libraries

Simple and intuitive Multiphysics Problem setup

Meshing

Solving

Visualization + Postprocessing

Data Import/Export

COMSOL is designed from the bottom up for arbitrary combinations of physical equations and easy user customization



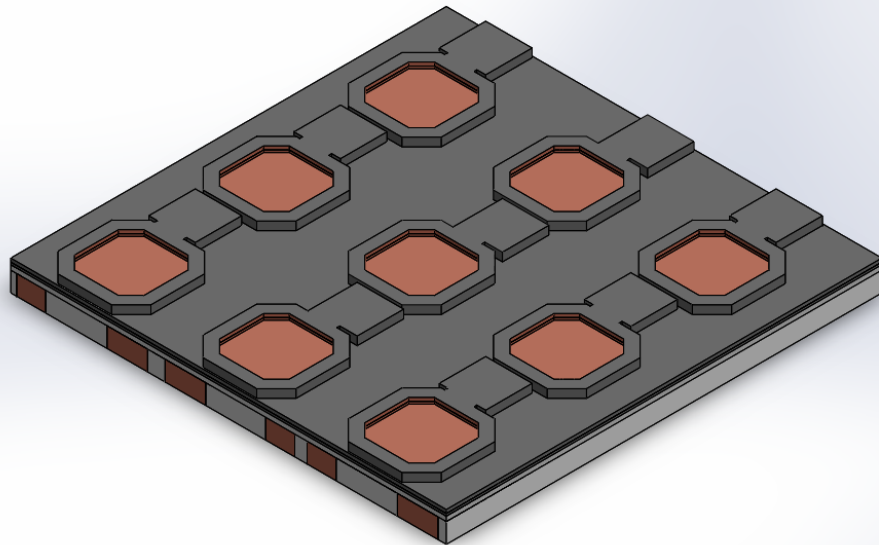
Geometry

CLICpix + CCPDv3 model

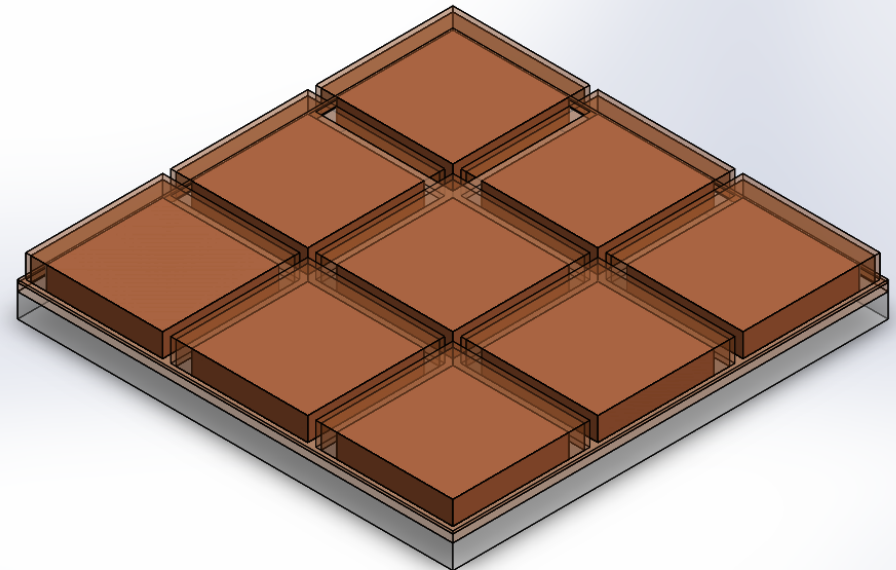
13

- Solidworks parts

CLICpix



CCPDv3



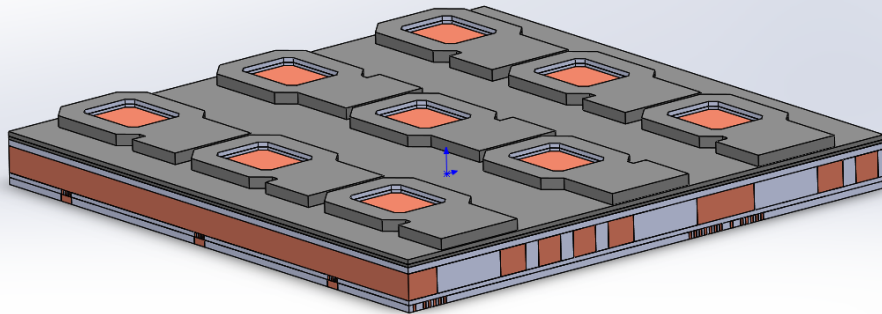
Geometry

CLICpix2 + C3PD model

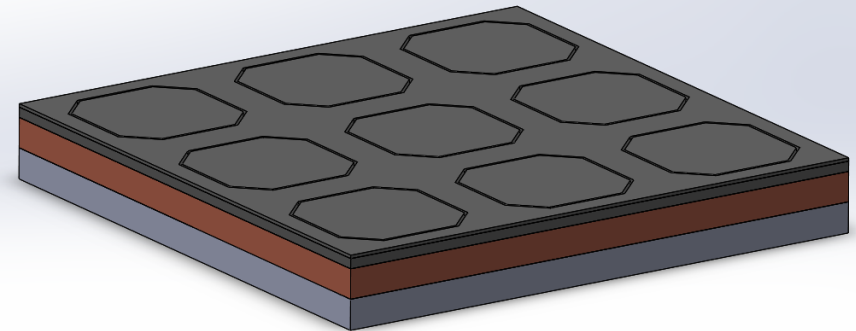
14

- Solidworks parts

CLICpix2



C3PD



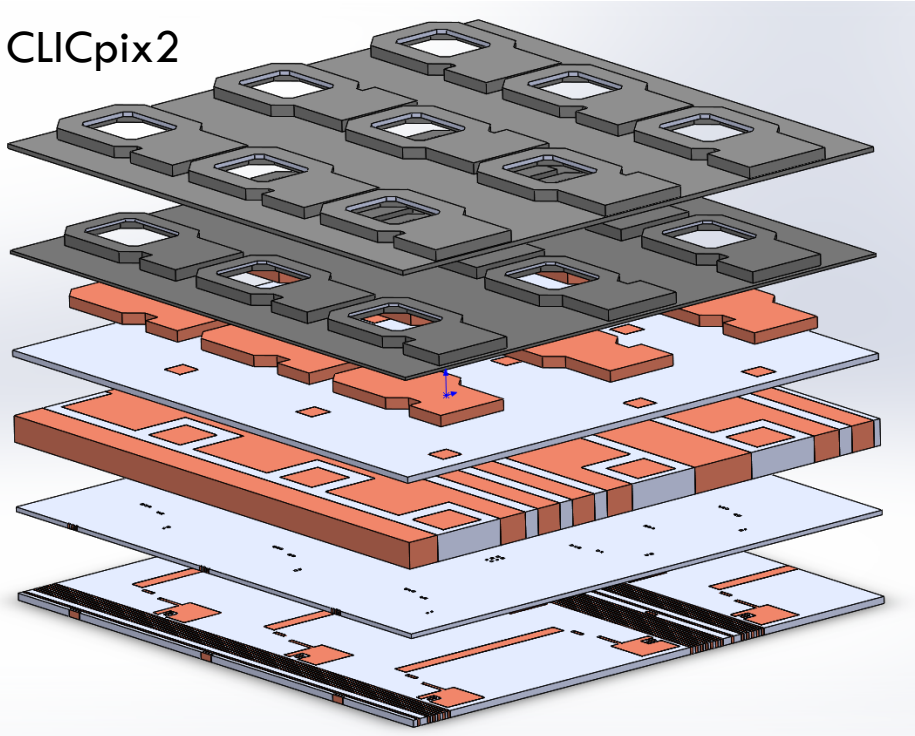
Geometry

CLICpix2 + C3PD model

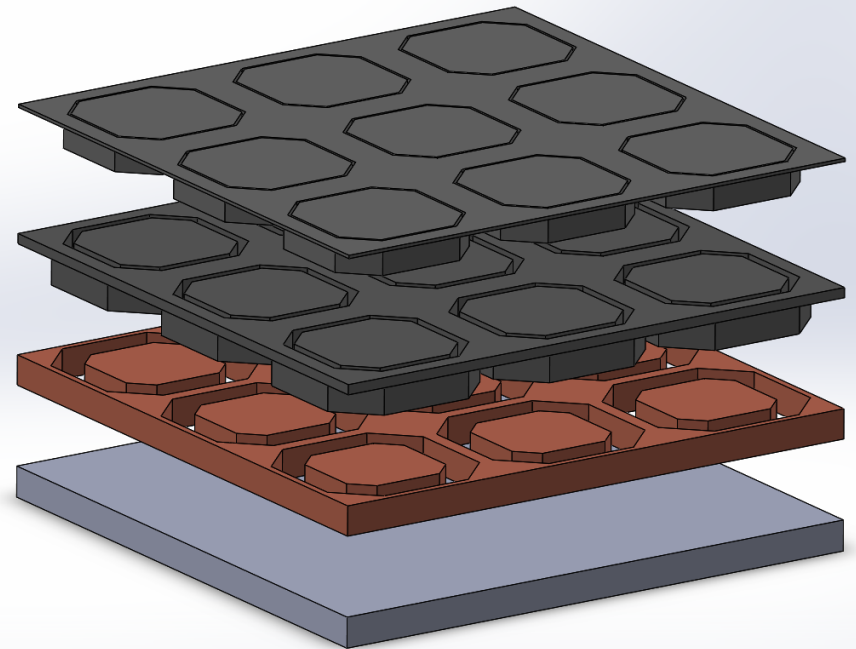
15

- Solidworks parts

CLICpix2



C3PD

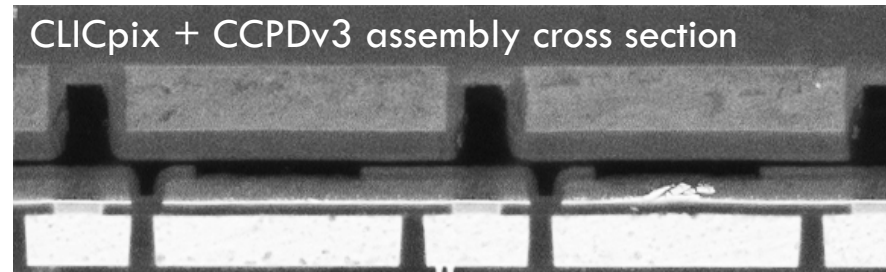
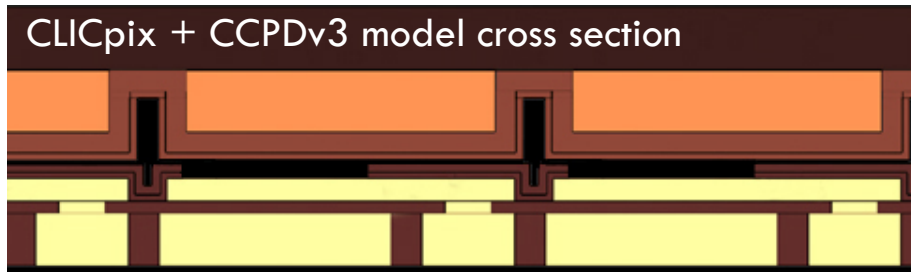
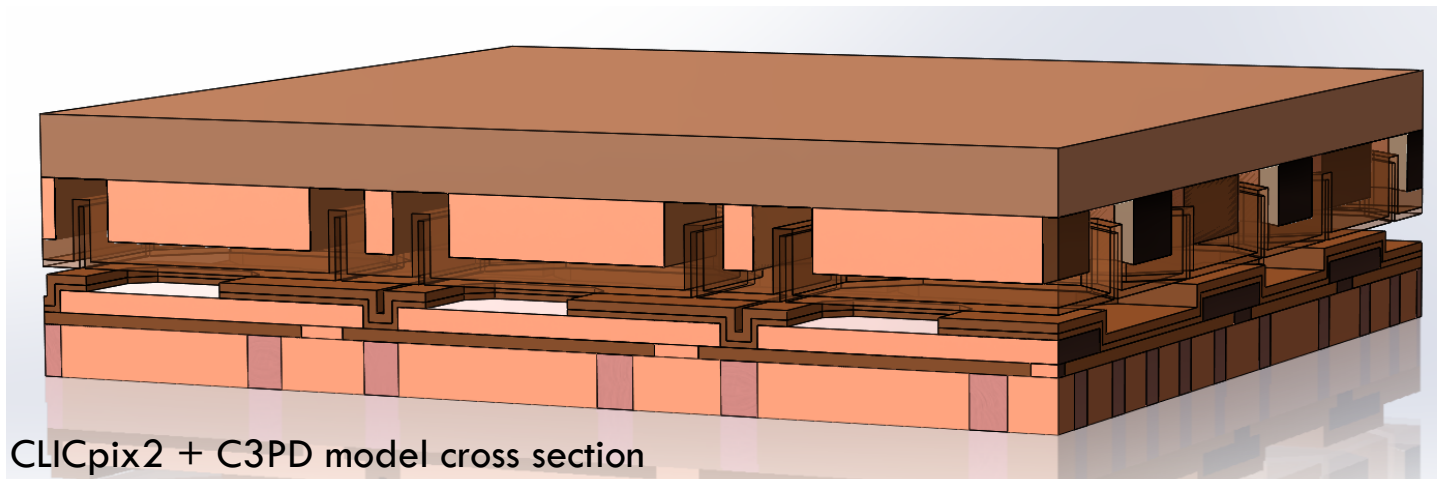


Geometry

Assembly model (gap = $0.22\mu\text{m}$)

16

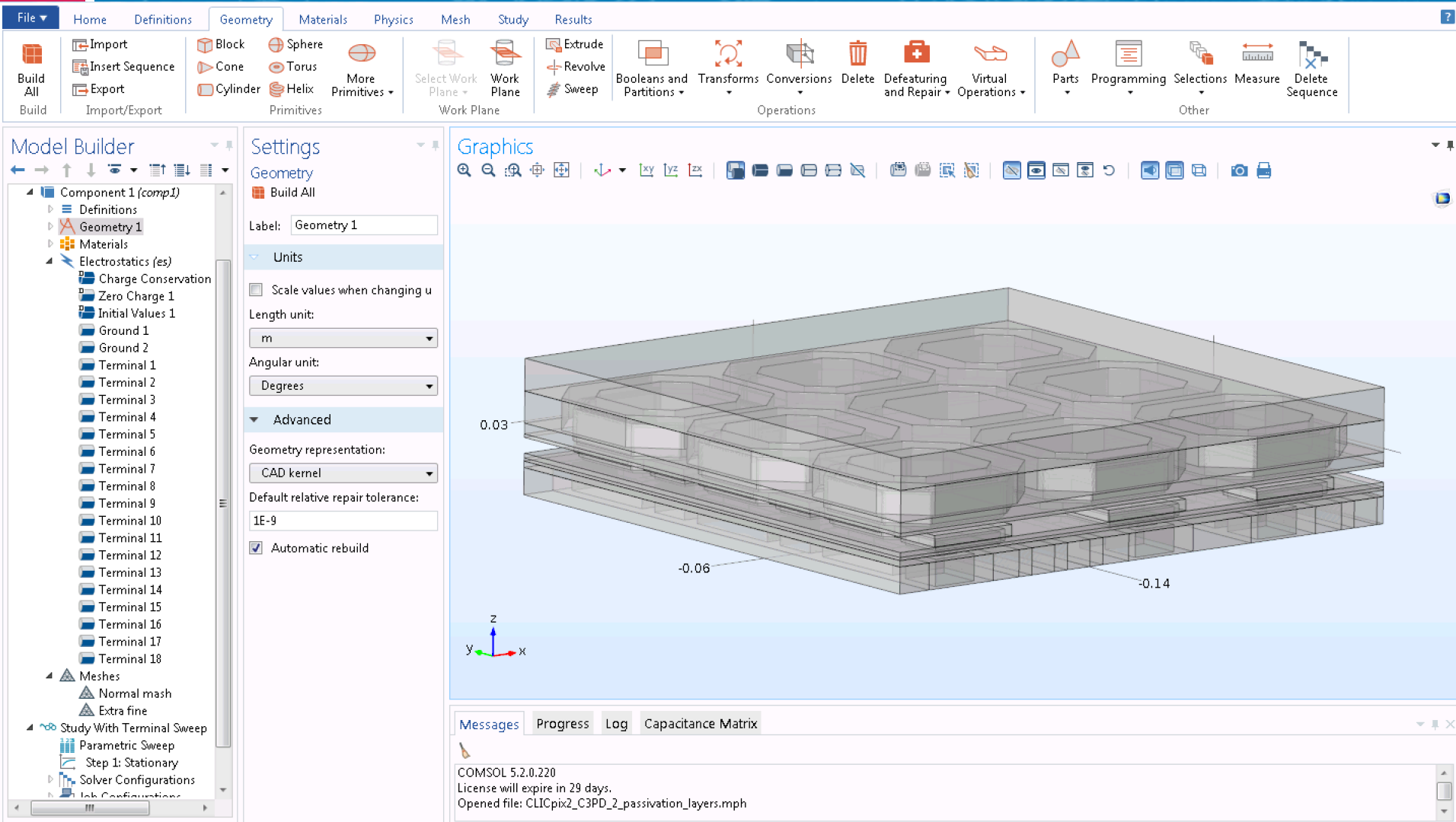
- HV-CMOS sensor on TOP and Read-out chip on BOTTOM



Geometry

Imported to COMSOL

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The screenshot displays the COMSOL Multiphysics software interface. The ribbon menu at the top includes tabs for File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The Geometry ribbon is active, showing various tools like Block, Sphere, Cone, Cylinder, Helix, Extrude, Revolve, Sweep, Booleans and Partitions, Transforms, Conversions, Delete, Defeaturing and Repair, and Virtual Operations.

The Model Builder tree on the left shows a hierarchy for Component 1 (comp1), including Definitions, Geometry 1, Materials, and Electrostatics (es). Under Electrostatics, there are sub-entities like Charge Conservation, Zero Charge 1, Initial Values 1, Ground 1-2, and Terminal 1-18.

The Settings panel for Geometry 1 is visible, showing options for Units (Length unit: m, Angular unit: Degrees), Advanced settings (Geometry representation: CAD kernel, Default relative repair tolerance: 1E-9, Automatic rebuild checked), and a Build All button.

The Graphics window shows a 3D perspective view of the imported geometry. The model consists of a base with a grid of hexagonal holes. Dimensions are indicated: 0.03 for the height of the top layer, -0.06 for the width of the base, and -0.14 for the depth. A coordinate system with x, y, and z axes is shown at the bottom left.

The Messages window at the bottom displays the following text:

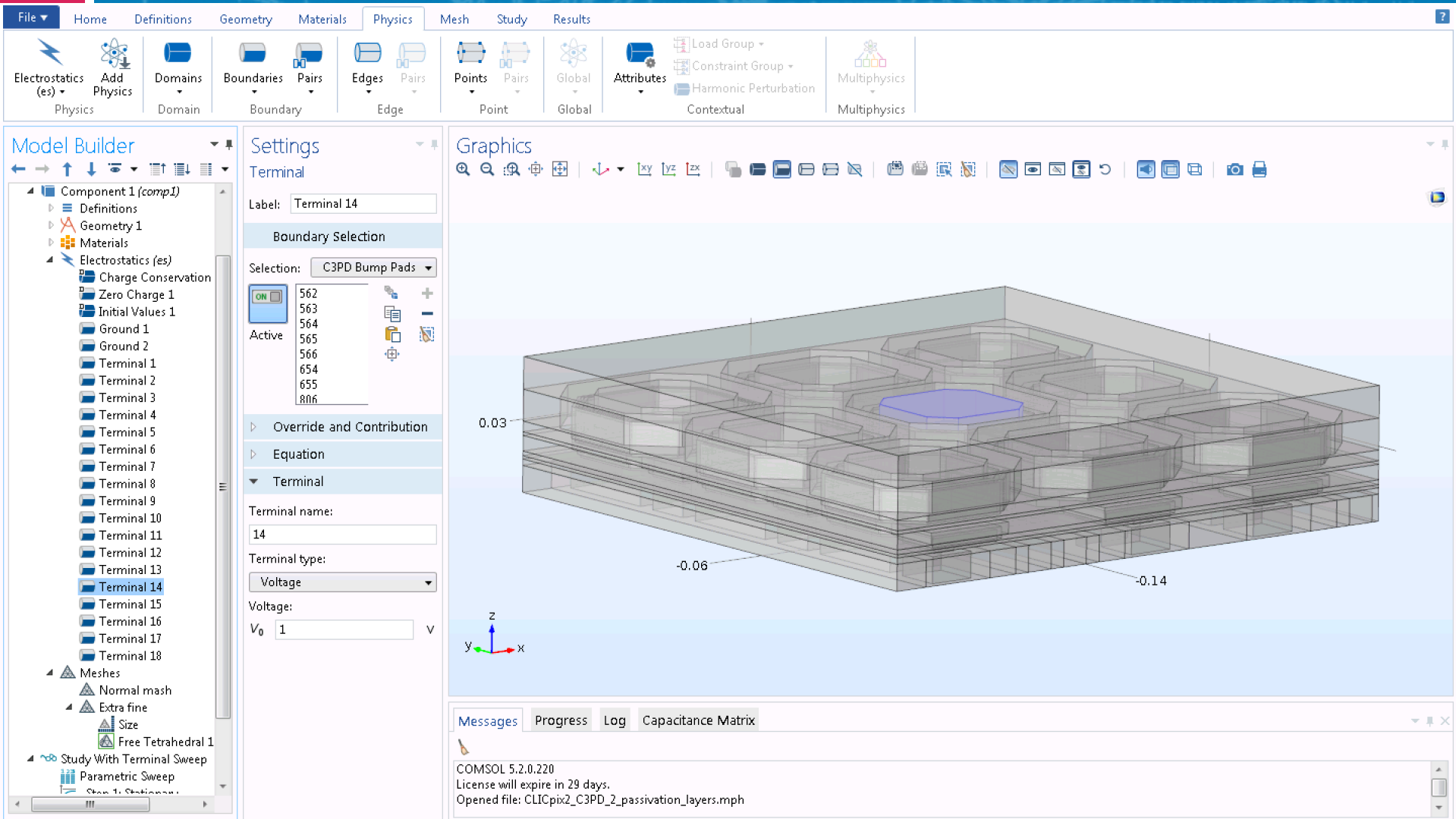
```

Messages Progress Log Capacitance Matrix
COMSOL 5.2.0.220
License will expire in 29 days.
Opened file: CLICpix2_C3PD_2_passivation_layers.mph
    
```

Simulation

COMSOL Multiphysics® - Pads/Terminals

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The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The Physics toolbar shows various physics settings, including Electrostatics (es), Add Physics, Domains, Boundaries, Pairs, Edges, Points, Global, Attributes, Load Group, Constraint Group, and Harmonic Perturbation. The Model Builder tree on the left shows a hierarchy of components, with Terminal 14 selected. The Settings panel for Terminal 14 is visible, showing the Boundary Selection as C3PD Bump Pads, a list of active boundaries (562-806), and the Terminal type set to Voltage with a value of 1 V. The Graphics window shows a 3D model of a circuit board with a central terminal highlighted in blue. The terminal is labeled with coordinates 0.03, -0.06, and -0.14. The Messages panel at the bottom shows the file name: CLICpix2_C3PD_2_passivation_layers.mph.

Simulation

COMSOL Multiphysics[®] - Metal lines (CLICpix2)

19

The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The Physics toolbar shows various physics settings, including Electrostatics (es), Add Physics, Domains, Boundaries, Pairs, Edges, Points, Global, Attributes, Load Group, Constraint Group, and Harmonic Perturbation. The Model Builder on the left shows a tree view for Component 1 (comp1), including Definitions, Geometry 1, Materials, and Electrostatics (es) with sub-items like Charge Conservation, Zero Charge 1, Initial Values 1, Ground 1, Ground 2, and Terminals 1 through 18. The Settings window for Terminal 14 is open, showing the Boundary Selection as C3PD Bump Pads. A table lists active IDs: 562, 563, 564, 565, 566, 654, 655, and 806. The Terminal name is 14, the Terminal type is Voltage, and the Voltage is set to 1 V. The Graphics window shows a 3D model of the metal lines. The Messages window at the bottom displays: COMSOL 5.2.0.220, License will expire in 29 days, and Opened file: CLICpix2_C3PD_2_passivation_layers.mph.

Simulation

COMSOL Multiphysics® - Mesh

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File Home Definitions Geometry Materials Physics Mesh Study Results

Build All Import Export Primitives Work Plane Operations Other

Model Builder

- Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Electrostatics (es)
 - Charge Conservation
 - Zero Charge 1
 - Initial Values 1
 - Ground 1
 - Ground 2
 - Terminal 1
 - Terminal 2
 - Terminal 3
 - Terminal 4
 - Terminal 5
 - Terminal 6
 - Terminal 7
 - Terminal 8
 - Terminal 9
 - Terminal 10
 - Terminal 11
 - Terminal 12
 - Terminal 13
 - Terminal 14
 - Terminal 15
 - Terminal 16
 - Terminal 17
 - Terminal 18
 - Meshes
 - Normal mesh
 - Extra fine
 - Size
 - Free Tetrahedral 1
 - Study With Terminal Sweep
 - Parametric Sweep
 - Step 1: Stationary

Settings

Size

Build Selected Build All

Label: Size

Element Size

Calibrate for: General physics

Predefined Extra fine

Custom

Element Size Parameters

Maximum element size: 2.63E-6 m

Minimum element size: 1.13E-7 m

Maximum element growth rate: 1.35

Curvature factor: 0.3

Resolution of narrow regions: 0.85

Graphics

0.03

-0.06

-0.14

Messages Progress Log Capacitance Matrix

COMSOL 5.2.0.220
License will expire in 29 days.
Opened file: CLICpix2_C3PD_2_passivation_layers.mph

Results

Capacitance Matrix

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- Coupling/Capacitance between all the terminals (pixel pads)

Table 10 Progress Log

CLIXpix2 terminals

Capacitance (fF)										CLIXpix2 terminals									
16.886	-0.39750	-1.5686E-8	-0.0014967	-5.7629E-5	-2.0997E-9	-4.2845E-10	-1.0636E-10	-7.7491E-13	-2.6928	-0.014929	-9.7037E-8	-0.0025388	-6.8890E-5	-1.2688E-8	-2.7128E-8	-4.9638E-9	-3.4026E-11		
-0.39750	17.667	-0.39743	-5.7600E-5	-0.0014657	-5.7607E-5	-6.2144E-11	-3.5882E-10	-1.0650E-10	-0.016202	-2.6776	-0.014920	-3.2961E-5	-0.0024986	-6.8794E-5	-3.5494E-9	-2.3491E-8	-4.9723E-9		
-1.5686E-8	-0.39743									-0.016198	-2.6927	-9.3946E-9	-3.2873E-5	-0.0025520	-2.4359E-11	-3.5197E-9	-2.8074E-8		
-0.0014967	-5.7600E-5									-6.8857E-5	-1.2669E-8	-2.6898	-0.014880	-8.5992E-8	-0.0030361	-5.0761E-5	-1.0888E-8		
-5.7630E-5	-0.0014657									-0.0024987	-6.8847E-5	-0.016120	-2.6746	-0.014876	-8.2951E-5	-0.0029634	-5.0759E-5		
-2.0996E-9	-5.7607E-5									-3.2961E-5	-0.0025536	-8.7869E-8	-0.016122	-2.6898	-1.4377E-8	-8.3040E-5	-0.0030222		
-4.2847E-10	-6.2143E-11									-4.9689E-9	-3.1233E-11	-0.0030362	-5.0752E-5	-1.0896E-8	-2.6923	-0.014942	-9.8739E-8		
-1.0637E-10	-3.5882E-11									-2.8627E-8	-4.9704E-9	-8.2976E-5	-0.0029644	-5.0760E-5	-0.016151	-2.6769	-0.014938		
-7.7481E-13	-1.0650E-11									-5.4247E-9	-3.3749E-8	-1.4350E-8	-8.3054E-5	-0.0030232	-9.7434E-8	-0.016157	-2.6923		
-2.6928	-0.016202									-0.030083	-2.9487E-6	-0.033500	-6.8671E-4	-3.6036E-7	-2.9691E-6	-3.6108E-7	-1.5354E-9		
-0.014929	-2.6776									7.0506	-0.030060	-6.8650E-4	-0.032827	-6.8641E-4	-3.6184E-7	-2.6066E-6	-3.6166E-7		
-9.7041E-8	-0.014920									-0.030061	6.9887	-3.6012E-7	-6.8610E-4	-0.033467	-1.5370E-9	-3.6180E-7	-2.9708E-6		
-0.0025387	-3.2961E-5									-6.8650E-4	-3.6010E-7	7.0538	-0.029399	-2.5881E-6	-0.033180	-6.8078E-4	-3.5927E-7		
-6.8890E-5	-0.0024987									-0.032827	-6.8610E-4	-0.029399	7.0835	-0.029376	-6.8142E-4	-0.032472	-6.8087E-4		
-1.2689E-8	-6.8793E-5									-6.8641E-4	-0.033467	-2.5881E-6	-0.029376	7.0533	-3.5956E-7	-6.8097E-4	-0.033181		
-2.7129E-8	-3.5492E-9	-2.4360E-11	-0.0030360	-8.2949E-5	-1.4376E-8	-2.6923	-0.016151	-9.7434E-8	-2.9692E-6	-3.6183E-7	-1.5373E-9	-0.033180	-6.8142E-4	-3.5954E-7	7.0201	-0.030088	-2.9502E-6		
-4.9640E-9	-2.3491E-8	-3.5195E-9	-5.0761E-5	-0.0029632	-8.3040E-5	-0.014942	-2.6769	-0.016157	-3.6109E-7	-2.6066E-6	-3.6180E-7	-6.8079E-4	-0.032472	-6.8096E-4	-0.030088	7.0499	-0.030073		
-3.4016E-11	-4.9721E-9	-2.8072E-8	-1.0888E-8	-5.0758E-5	-0.0030223	-9.8737E-8	-0.014938	-2.6923	-1.5355E-9	-3.6165E-7	-2.9707E-6	-3.5927E-7	-6.8087E-4	-0.033181	-2.9502E-6	-0.030073	7.0196		

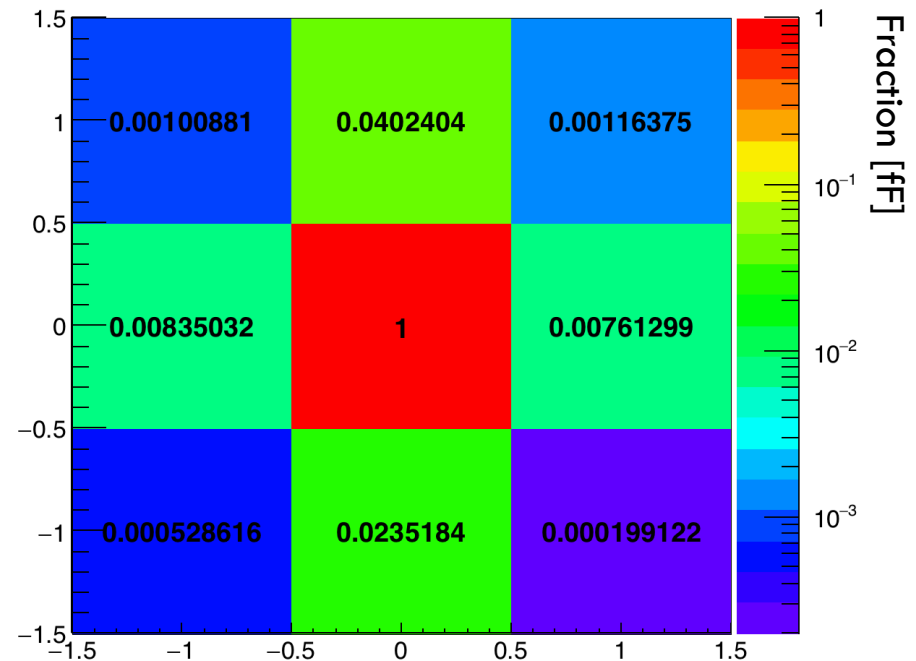
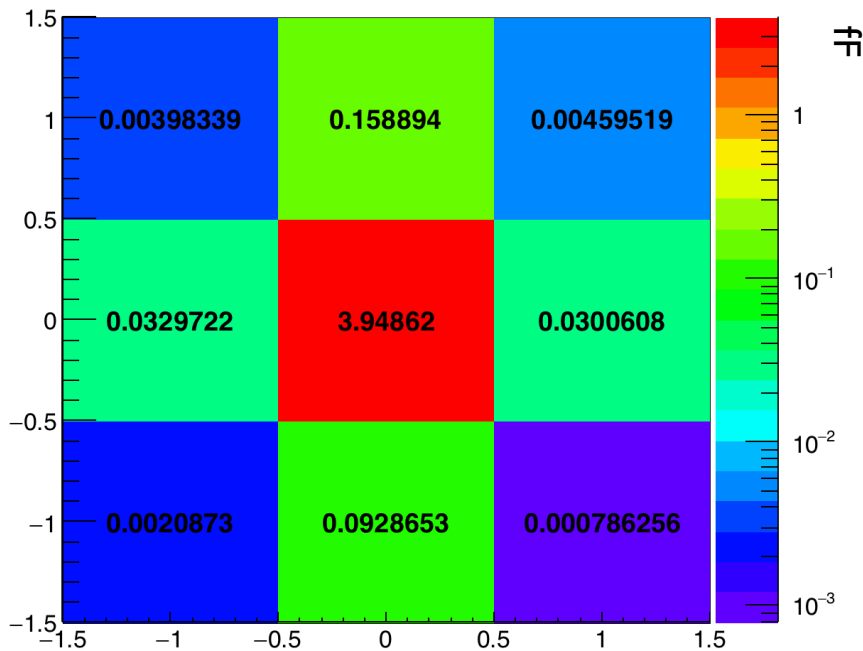
C3PD terminals

Results

Capacitance Matrix – CCPDv3 → CLICpix

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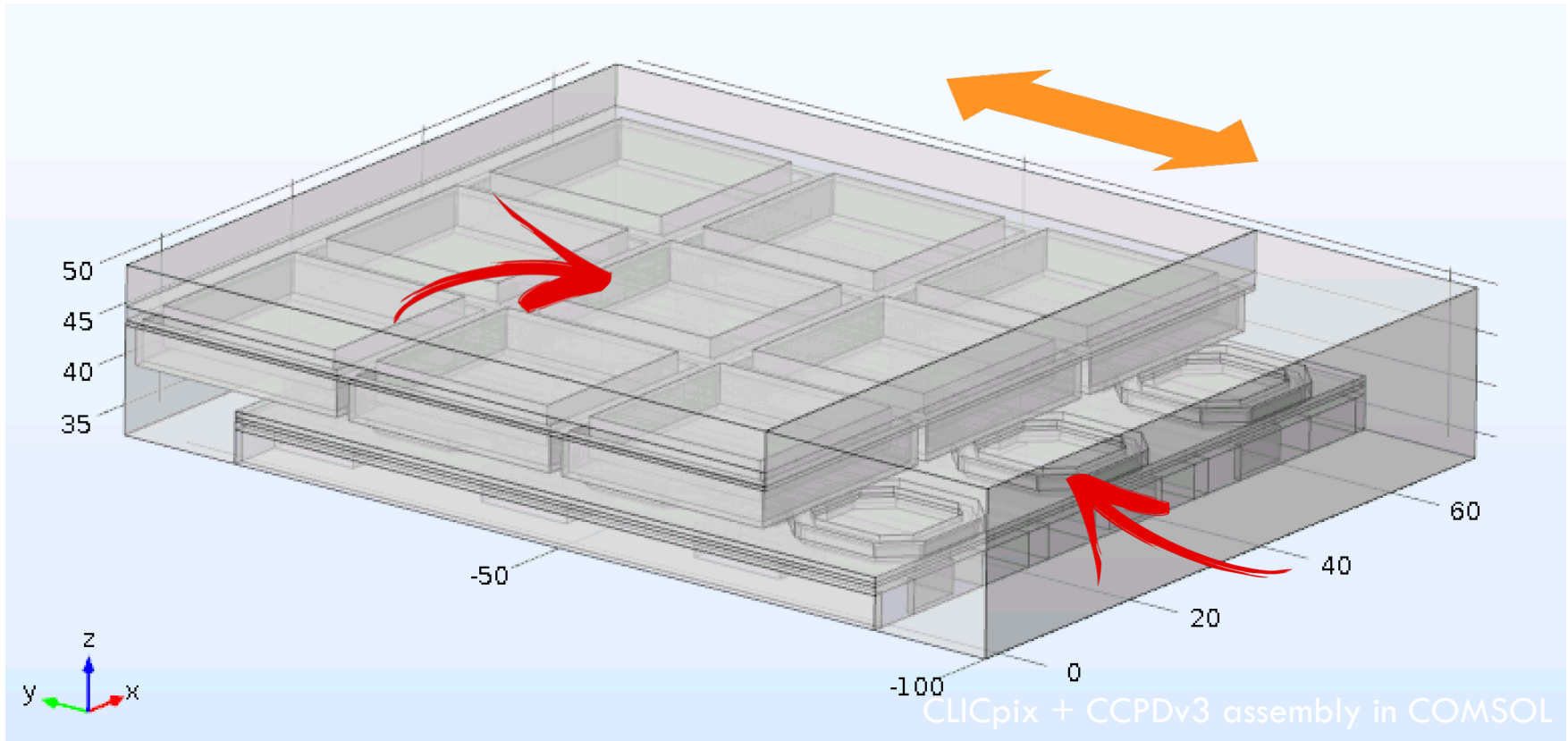
- Coupling between central pixel in CCPDv3 and other 9 pixels in the CLICpix chip
 - ▣ Fraction on right plot: $C_i = C_i / C_{\text{center}}$
- Asymmetric coupling with central top and bottom pixels (difference ~2%)



Alignment Scan

Problem with the 3x3 matrix

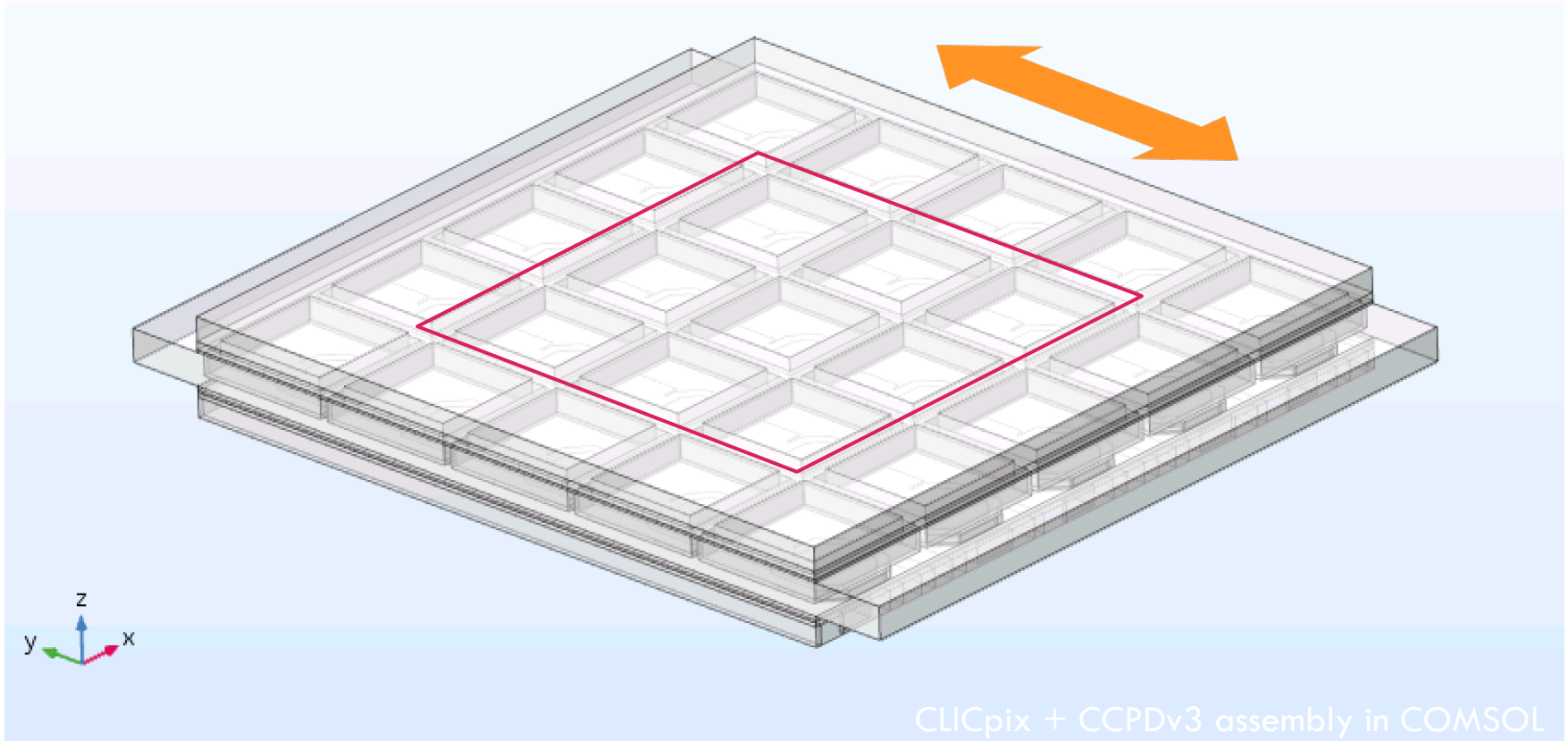
23



Alignment Scan

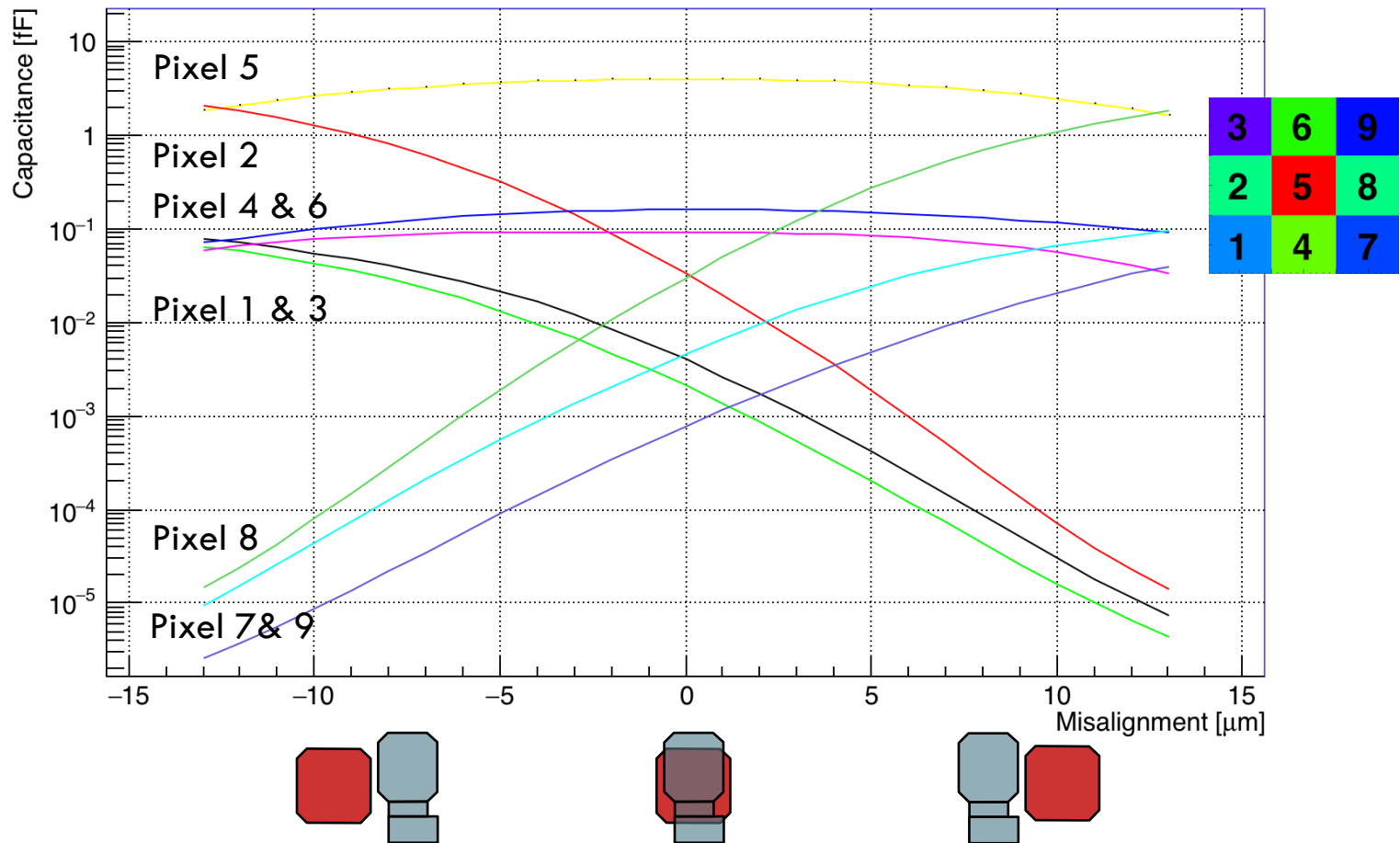
5x5 matrix, checking 3x3 central pixels

24



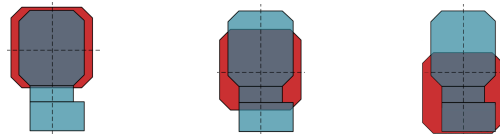
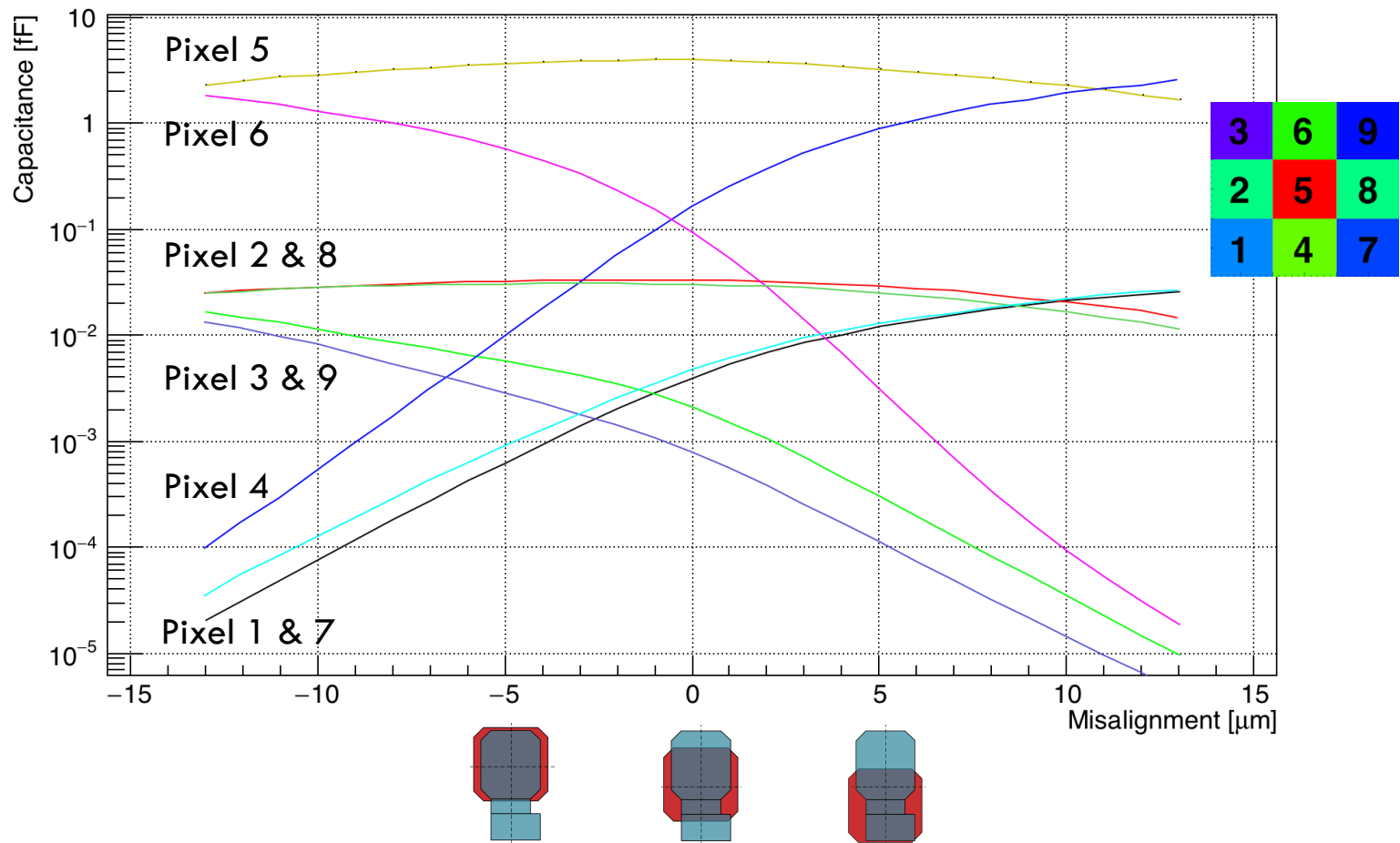
Effect on X-direction Misalignment

Cross Pixel Coupling (CCPDv3 → CLICpix)



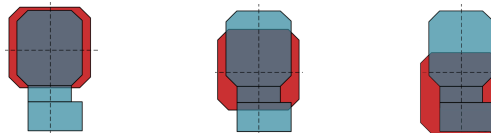
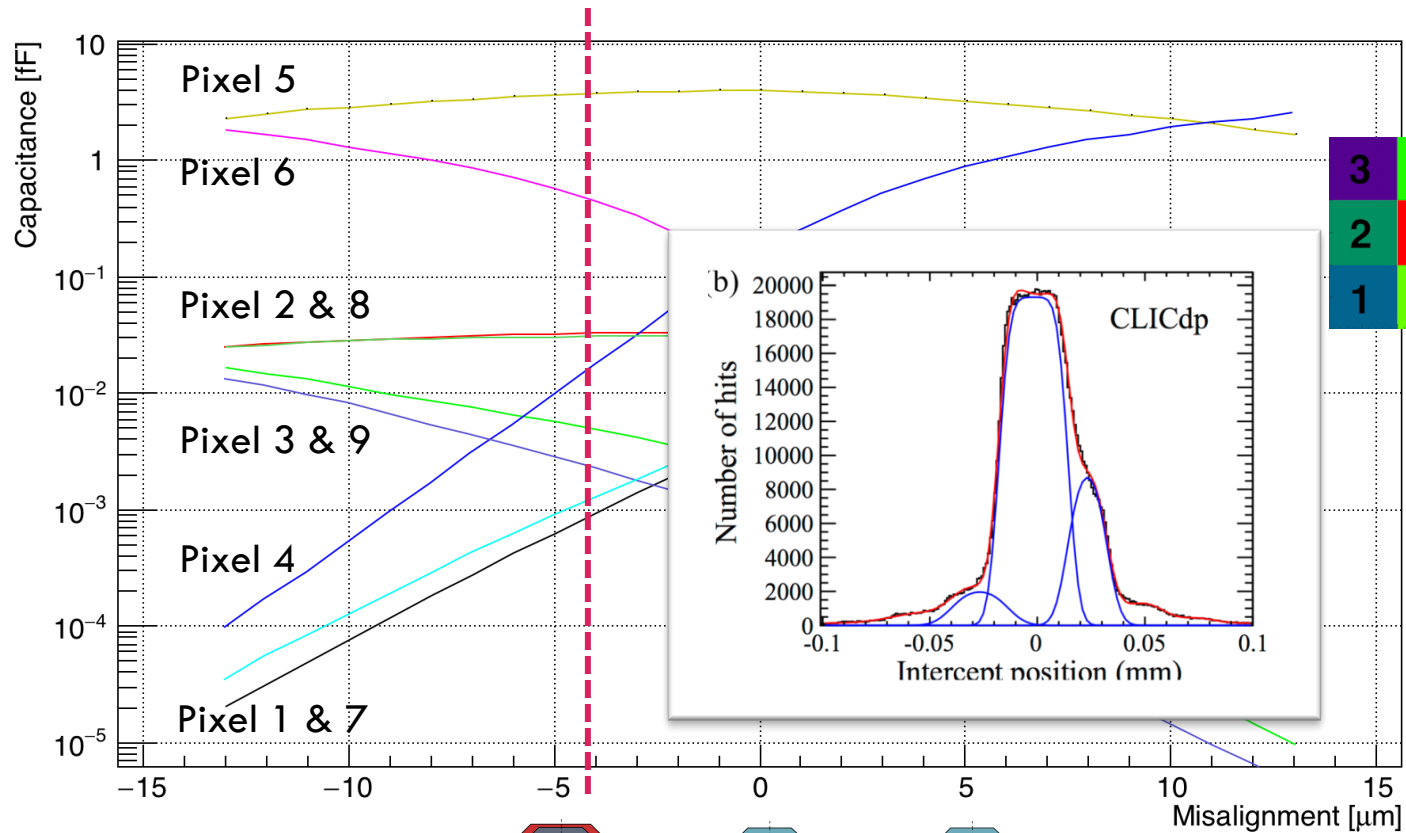
Effect on Y-direction Misalignment

Cross Pixel Coupling (CCPDv3 → CLICpix)



Effect on Y-direction Misalignment

Cross Pixel Coupling (CCPDv3 → CLICpix)

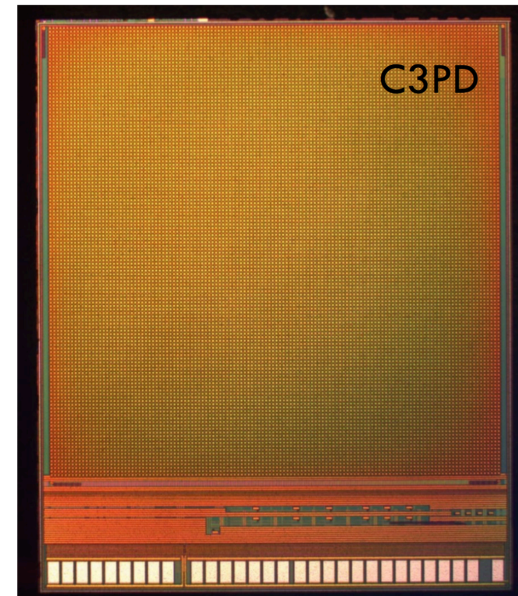
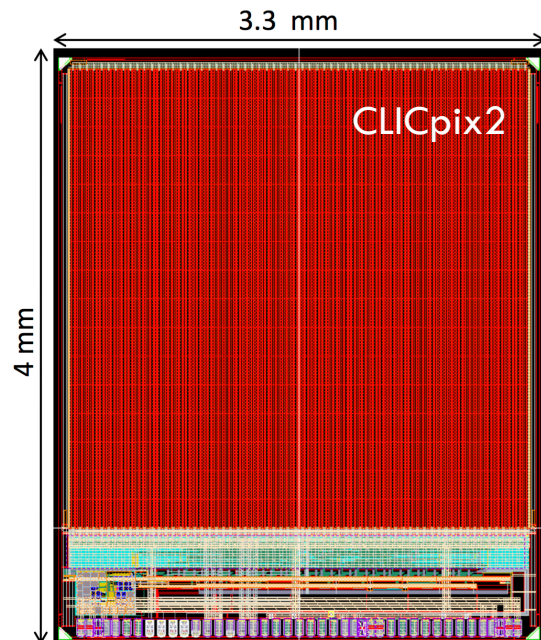


New Chips

CLICpix2 and C3PD

28

- Improved chips based on previous CLICpix and CCPDv3
 - ▣ Bigger pixel matrix
 - ▣ Different pixel electronics
 - ▣ Guard ring around HV-CMOS pixels pads

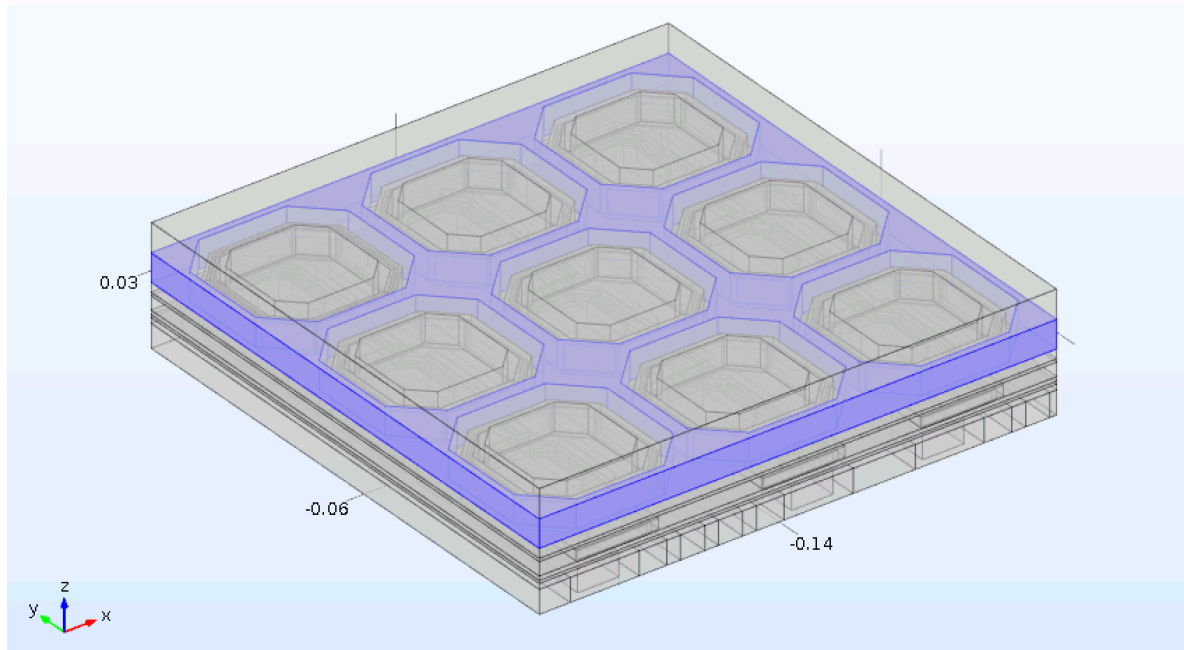


CLICpix2/C3PD Simulation

Guard Ring

29

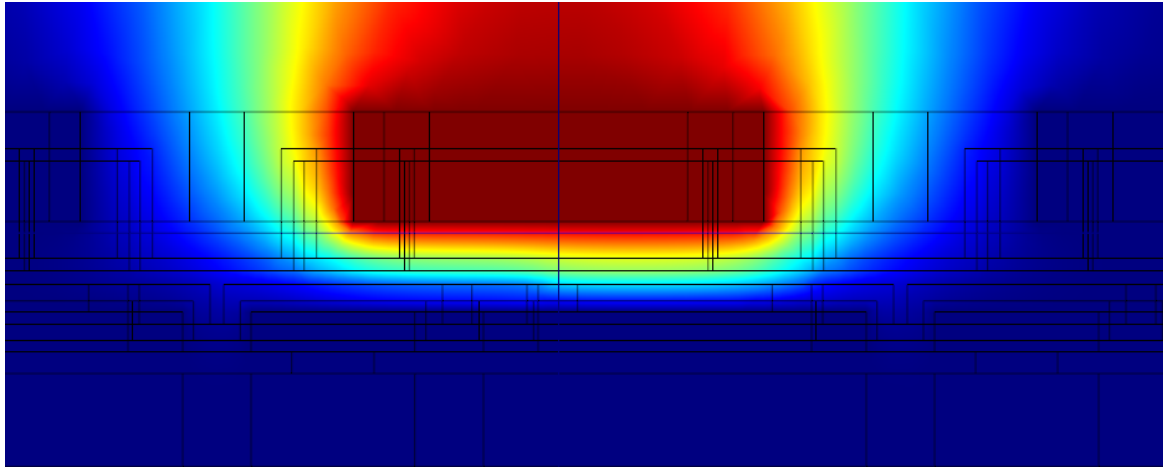
- With Guard Ring
 - ▣ Selected solid = Aluminium; **Terminal/Grounded**
- Without Guard Ring
 - ▣ Selected solid = Silica Glass; **Dielectric Coefficient = 2.09**



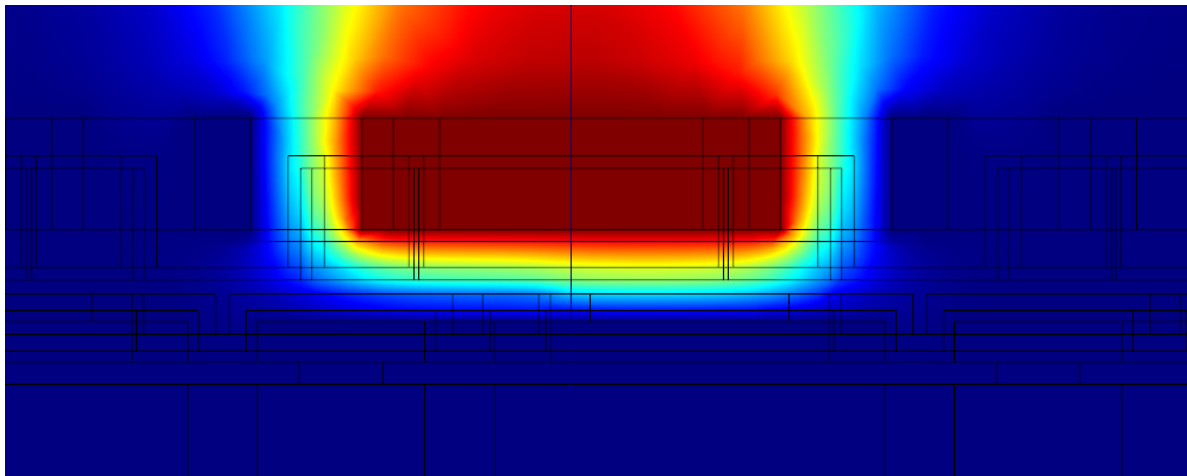
Results

without Guard Ring – Electric Potential

Without Guard Ring



With Guard Ring

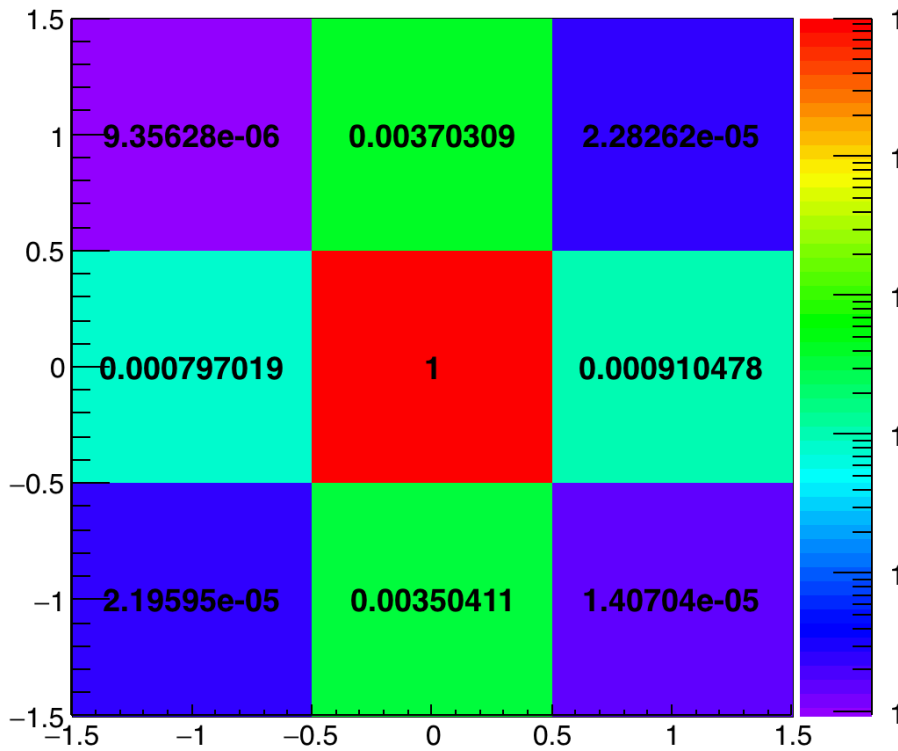


Results

C3PD → CLICpix2

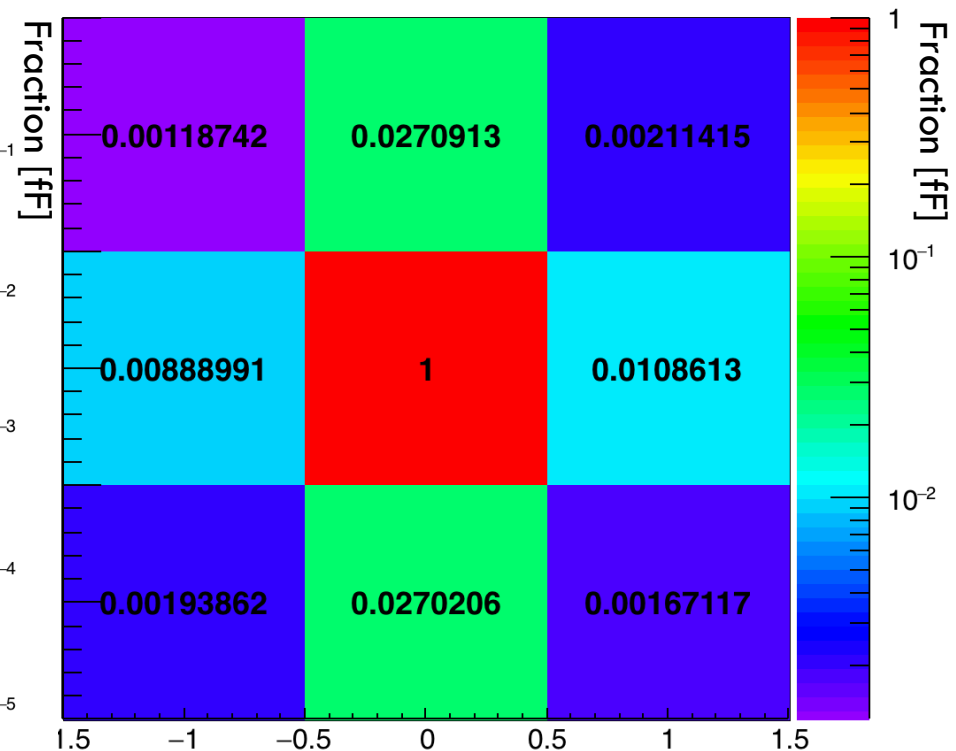
With Guard Ring

Central C3PD Pixel and CLIXpix2 terminals



Without Guard Ring

Central C3PD Pixel and CLIXpix2 terminals



CROSS CAPACITANCE INCREASES ~10X!

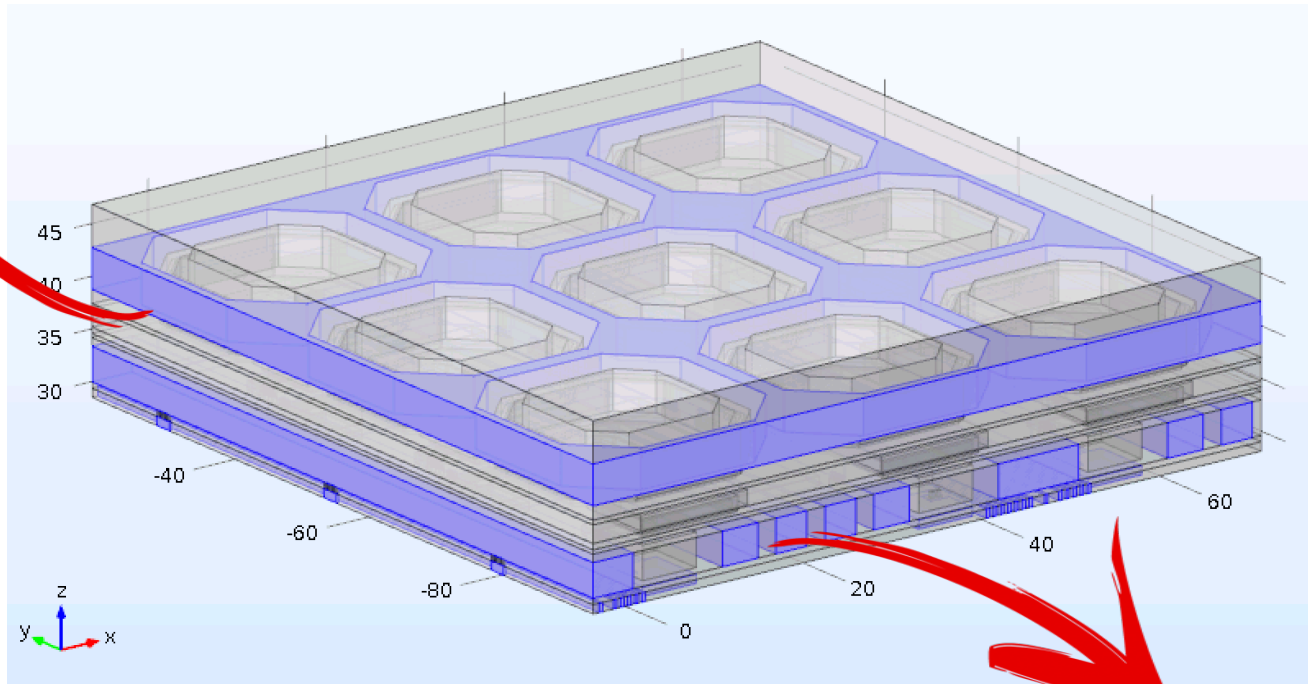
Results

Capacitive Coupling to other metals

32

- Coupling of the central pixel in the C3PD chip with the Guard Ring and M6+M5

GR: 3.14 fF

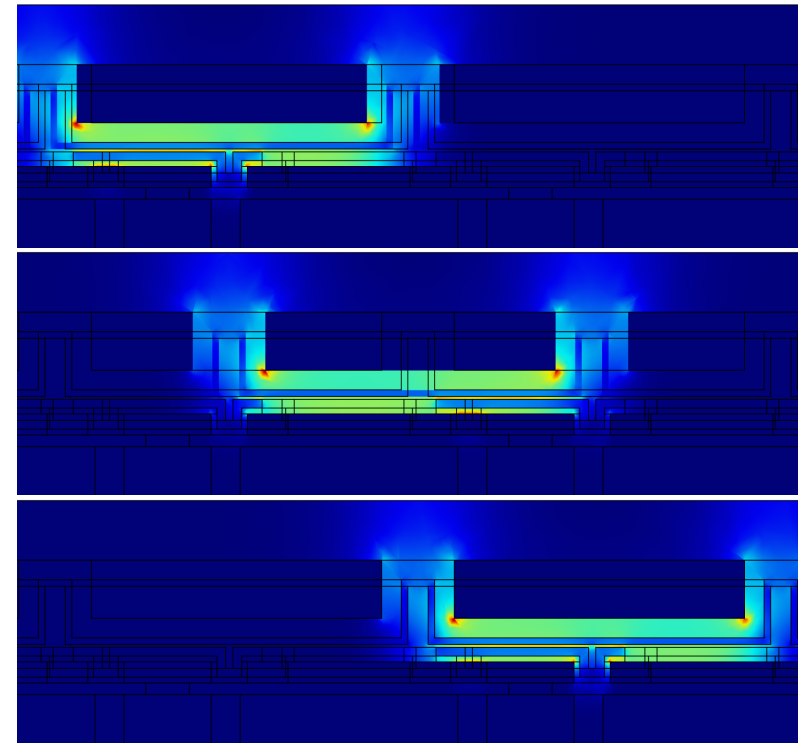


M6+M5: 0.39 fF

Conclusions and next steps

33

- Maxwell Capacitance Matrix
 - ▣ Figure of merit of coupling between chips
- Chips 3D model using SolidWorks
 - ▣ CLICpix + CCPDv3; CLICpix2 + C3PD
- COMSOL
 - ▣ A nice simulation software suite
 - ▣ Definition of terminals and metal layers + meshing
- Results
 - ▣ Coupling between the pixels
 - ▣ Effect of Guard-Rings around pixel pads
 - ▣ Misalignment effects

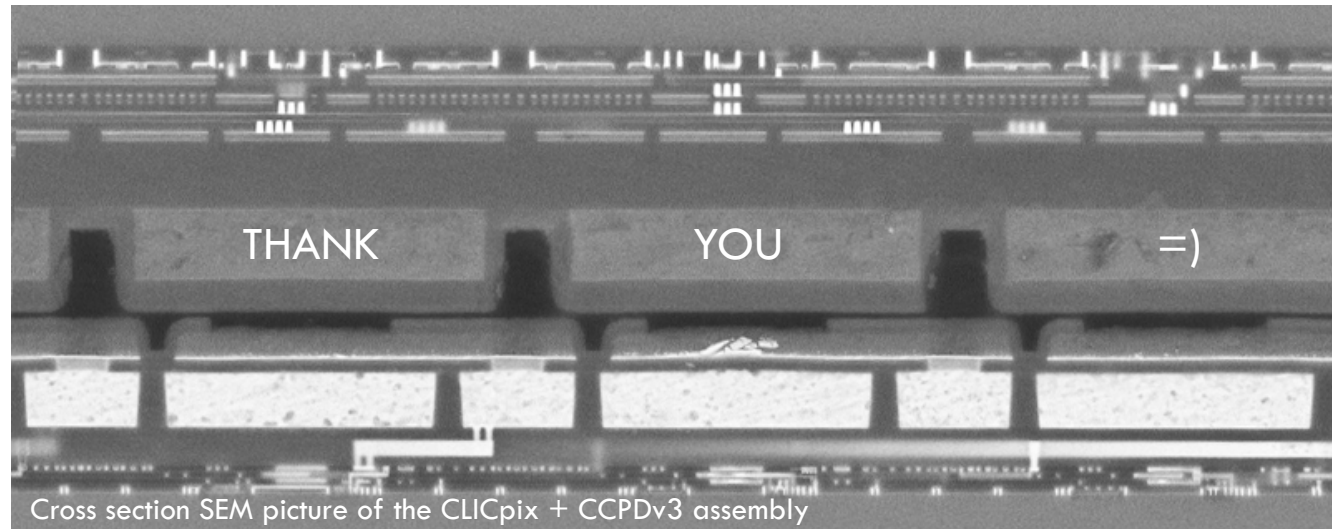


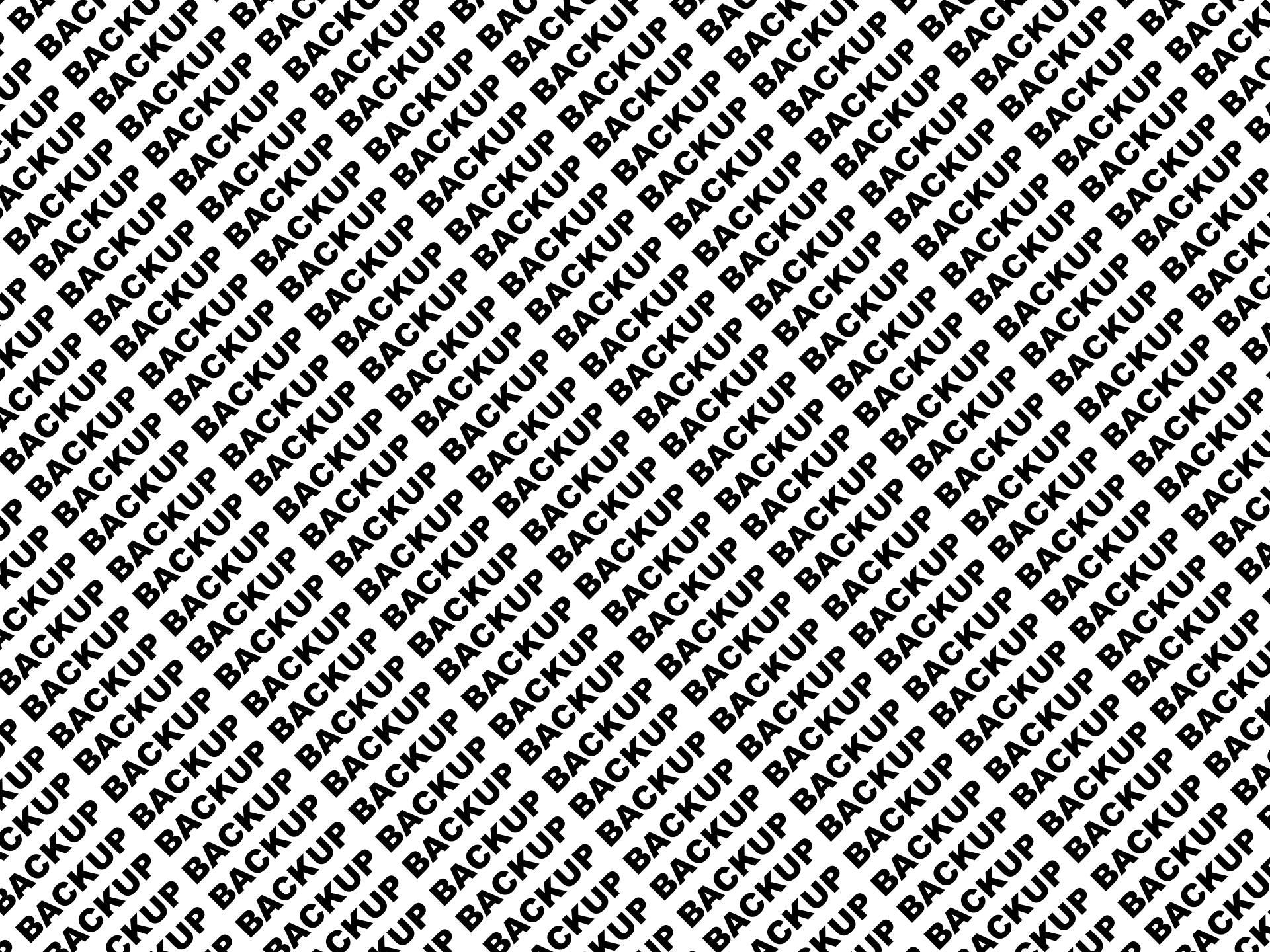
CCPDv3 shifting from -13 to 13 μm away from ideal alignment.
Color scale shows the electric field norm.

Conclusions and next steps

34

- Next Steps
 - ▣ Analyze the misalignment effect in data from test beam
 - ▣ Create a digitizer for HV-CMOS sensors
 - Simulate, using TCAD/AllPix/Geant4, the readout chain
 - Optimize pixel pads geometry; induced charge sharing effects and etc...



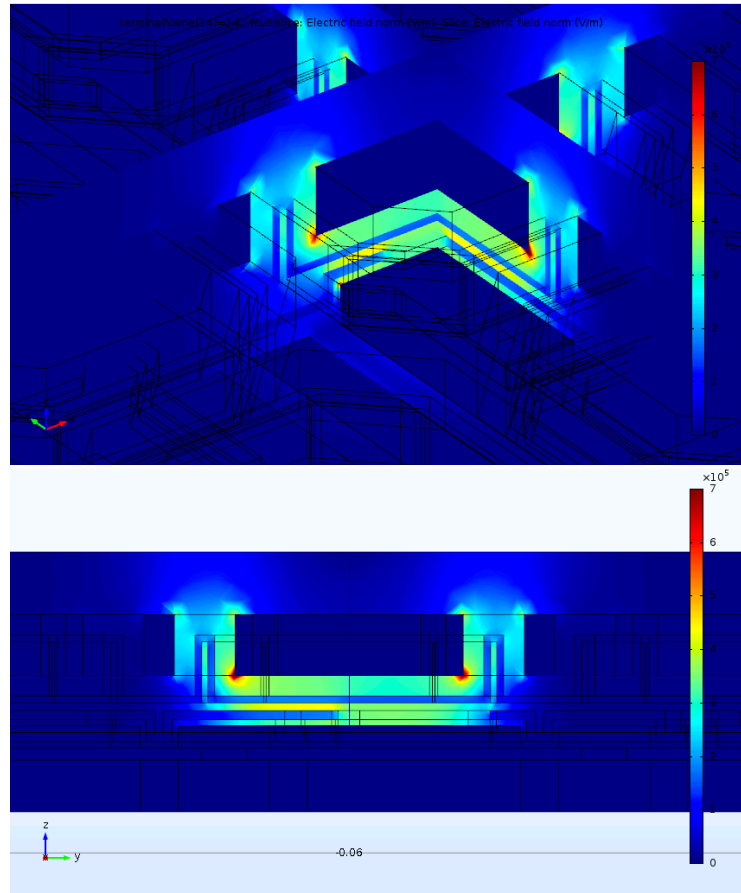


Results

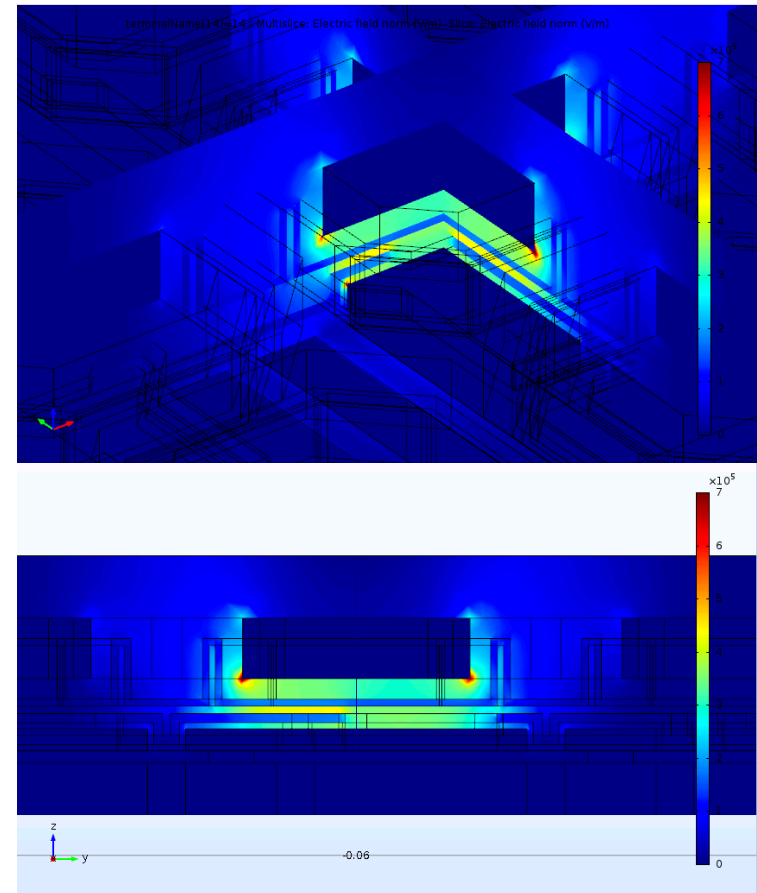
without Guard Ring – Electric Field

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With Guard Ring



Without Guard Ring



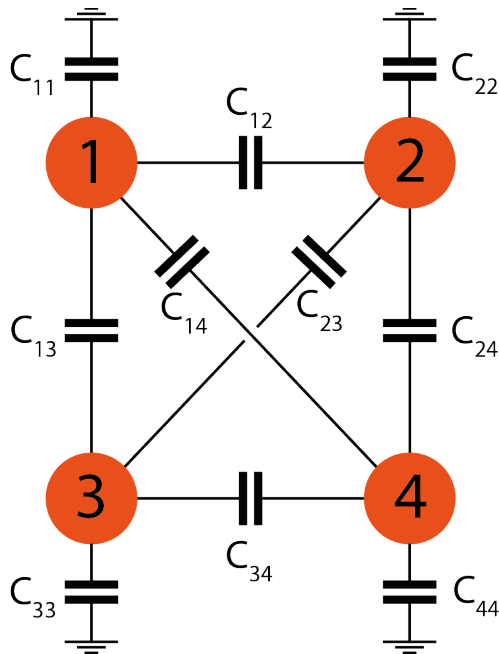
Objective

37

□ Calculate the capacitance between pixels in the CLICpix2 and C3PD chips

▣ Maxwell Capacitance Matrix

■ E. Di Lorenzo, FastFieldSolvers, *The Maxwell Capacitance Matrix*, White Paper WP110301



$$Q_i = \sum_{j=1}^{N+1} C_{ij} \varphi_j$$

$$Q_1 = C_{11} \cdot V_1 + C_{12} \cdot (V_1 - V_2) + C_{13} \cdot (V_1 - V_3) + C_{14} \cdot (V_1 - V_4)$$

$$Q_1 = (C_{11} + C_{12} + C_{13} + C_{14}) \cdot V_1 - C_{12} \cdot V_2 - C_{13} \cdot V_3 - C_{14} \cdot V_4$$

$$\begin{vmatrix} C_{11} + C_{12} + C_{13} + C_{14} & -C_{12} & -C_{13} & -C_{14} \end{vmatrix}$$

$$\begin{bmatrix} C_{11} + C_{12} + C_{13} + C_{14} & -C_{12} & -C_{13} & -C_{14} \\ -C_{21} & C_{21} + C_{22} + C_{23} + C_{24} & -C_{23} & -C_{24} \\ -C_{31} & -C_{32} & C_{31} + C_{32} + C_{33} + C_{34} & -C_{34} \\ -C_{41} & -C_{42} & -C_{43} & C_{41} + C_{42} + C_{43} + C_{44} \end{bmatrix}$$

$$\begin{bmatrix} C_{11} + C_{12} + \dots + C_{1n} & -C_{12} & \dots & -C_{1n} \\ -C_{21} & C_{21} + C_{22} + \dots + C_{2n} & \dots & -C_{2n} \\ \dots & \dots & \dots & \dots \\ -C_{m1} & -C_{n2} & \dots & C_{n1} + C_{n2} + \dots + C_{nn} \end{bmatrix}$$

Capacitance

and its geometrical nature (quantitatively)

35

arXiv:physics/0702253

$$Q_i = \oint_{S_i} \sigma_i dS = -\epsilon_0 \oint_{S_i} \nabla \phi \cdot \mathbf{n}_i dS, \quad (1) \quad \sigma_i = \epsilon_0 \mathbf{E} \cdot \mathbf{n}_i = -\epsilon_0 \nabla \phi \cdot \mathbf{n}_i$$

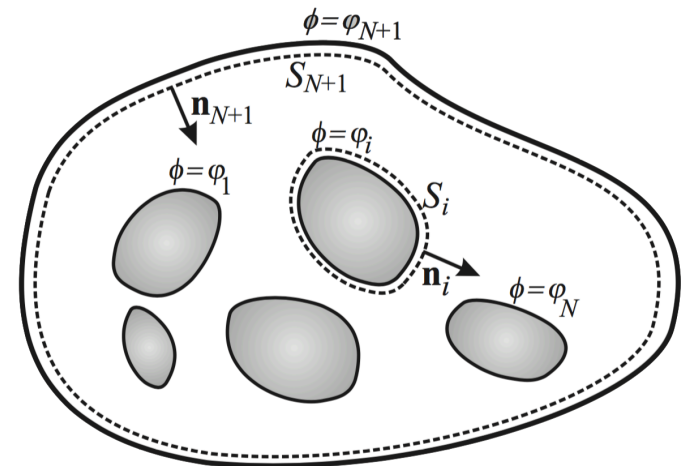
$$\phi(S_i) = \varphi_i, \quad \phi = \sum_{j=1}^{N+1} \varphi_j f_j \quad f_j(S_i) = \delta_{ij} \quad (2)$$

Potential depends only on the chosen surface!

Applying grad in (2) and replacing it in (1)

$$Q_i = -\epsilon_0 \sum_{j=1}^{N+1} \oint_{S_i} \varphi_j f_j \cdot \mathbf{n}_i dS = \sum_{j=1}^{N+1} C_{ij} \varphi_j$$

$$C_{ij} \equiv -\epsilon_0 \oint_{S_i} \nabla f_j \cdot \mathbf{n}_i dS$$



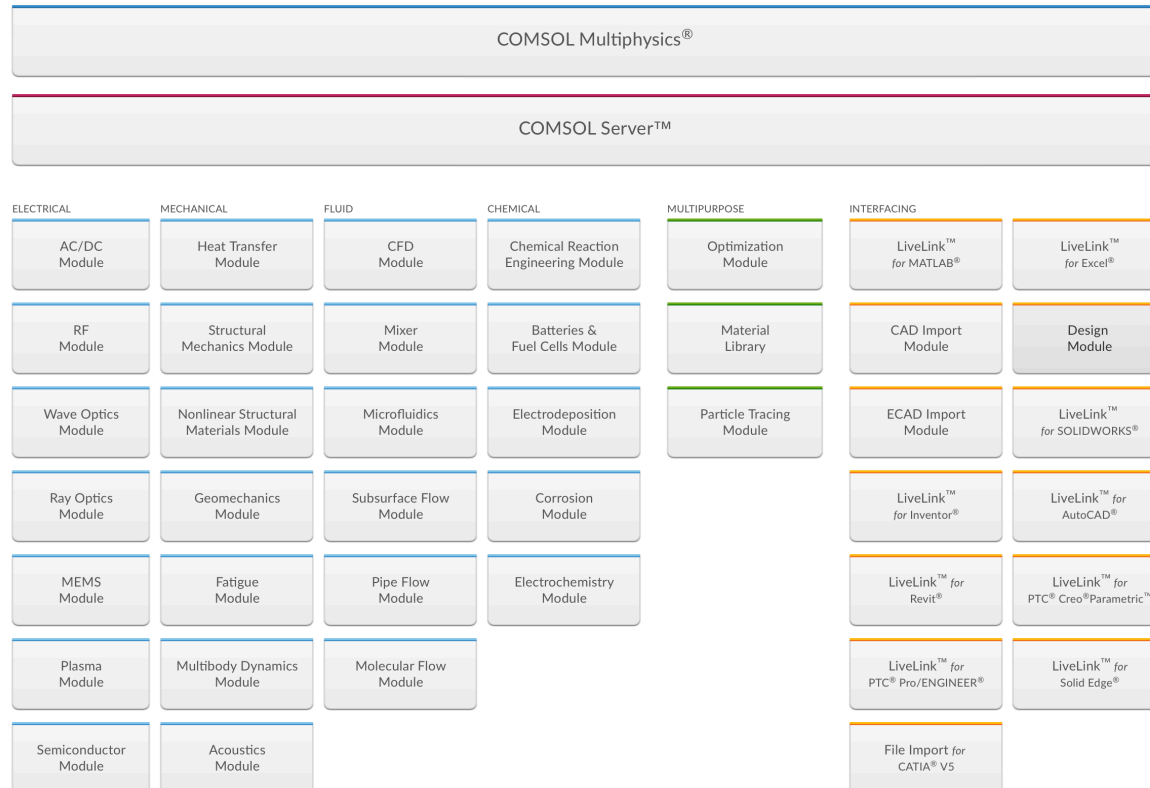
$$S_T = S_1 + \dots + S_N + S_{N+1}$$

Simulation

COMSOL Multiphysics®

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- Simulation Tool for Electrical, Mechanical, Fluid Flow, and Chemical Applications
 - Arbitrarily include **equations** describing a **material property**, **boundary**, **source** or **sink** term, or a unique set of **partial differential equations**

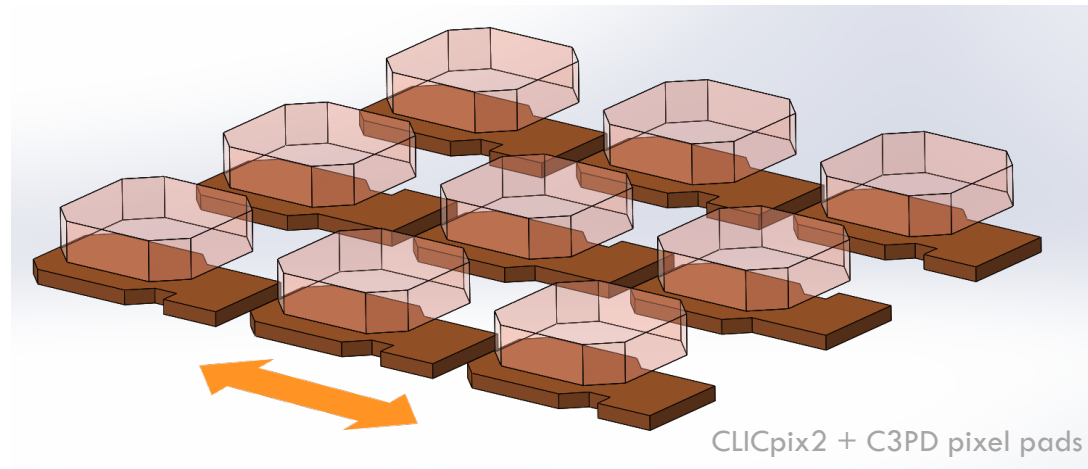
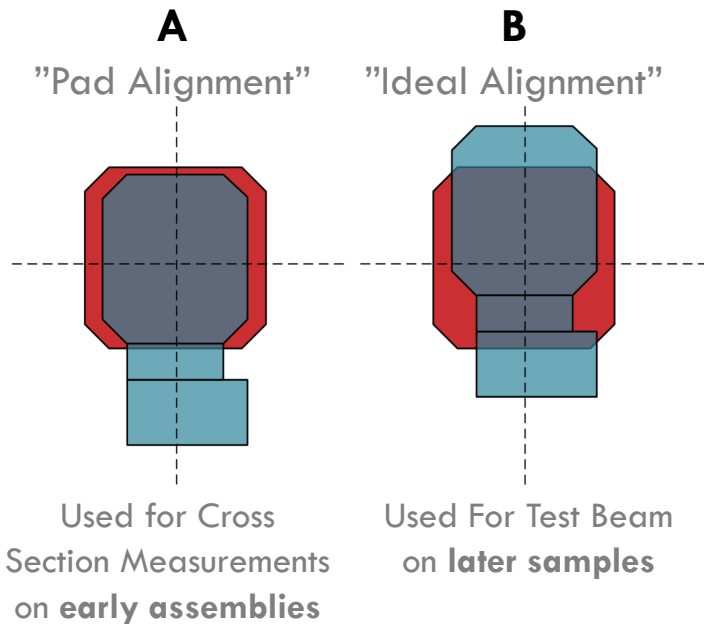


Chips Alignment

Two proposals

40

- Two alignment marks on the two sides of the chips
 - ▣ two different implementations of the alignment



Geometry

Empty space = Glue Layer (2 μ m)

41

The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The ribbon below the menu bar contains various tool icons categorized into Build, Import/Export, Primitives, Work Plane, Operations, and Other. The left sidebar shows the Model Builder tree with a hierarchy: Component 1 (comp1) > Definitions > Geometry 1 > Materials > Electrostatics (es) > Charge Conservation > Zero Charge 1 > Initial Values 1 > Ground 1 > Ground 2 > Terminal 1 through Terminal 18 > Meshes > Normal mash > Extra fine > Study With Terminal Sweep > Parametric Sweep > Step 1: Stationary > Solver Configurations > Job Configurations.

The Settings panel for Geometry 1 is visible, showing the following options:

- Label: Geometry 1
- Units:
 - Scale values when changing u:
 - Length unit: m
 - Angular unit: Degrees
- Advanced:
 - Geometry representation: CAD kernel
 - Default relative repair tolerance: 1E-9
 - Automatic rebuild:

The Graphics panel shows a 3D model of a rectangular substrate with a grid of eight raised, hexagonal-shaped structures. Dimension lines indicate a height of 0.03, a width of -0.06, and a depth of -0.14. A 3D coordinate system with x, y, and z axes is shown at the bottom left of the graphics area.

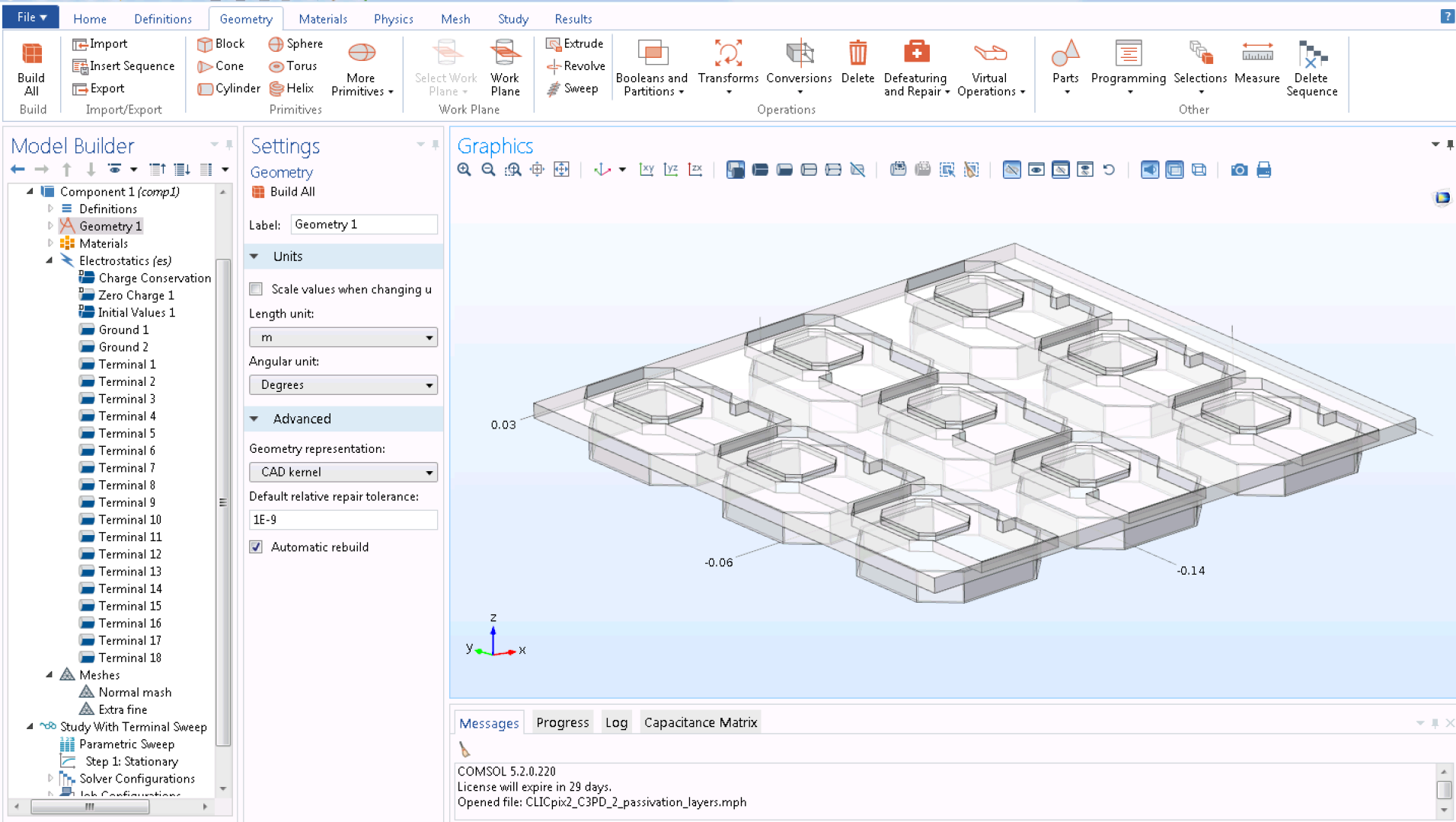
The Messages panel at the bottom displays the following text:

COMSOL 5.2.0.220
License will expire in 29 days.
Opened file: CLICpix2_C3PD_2_passivation_layers.mph

Geometry

Empty space = Glue Layer (2 μ m)

42



The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The ribbon contains various toolbars for modeling and simulation, such as Primitives, Operations, and Other.

The **Model Builder** on the left shows a tree structure for **Component 1 (comp1)**, including **Definitions**, **Geometry 1**, **Materials**, **Electrostatics (es)** (with sub-items like Charge Conservation, Zero Charge 1, Initial Values 1, Ground 1-2, Terminal 1-18), **Meshes** (Normal mash, Extra fine), and **Study With Terminal Sweep** (Parametric Sweep, Step 1: Stationary, Solver Configurations, Job Configurations).

The **Settings** panel for **Geometry 1** is visible, showing:

- Label: Geometry 1
- Build All
- Units:
 - Scale values when changing u:
 - Length unit: m
 - Angular unit: Degrees
- Advanced:
 - Geometry representation: CAD kernel
 - Default relative repair tolerance: 1E-9
 - Automatic rebuild:

The **Graphics** window shows a 3D perspective view of a complex, multi-layered PCB structure with several circular vias and rectangular pads. Dimensions are indicated: 0.03, -0.06, and -0.14. A coordinate system (x, y, z) is shown at the bottom left.

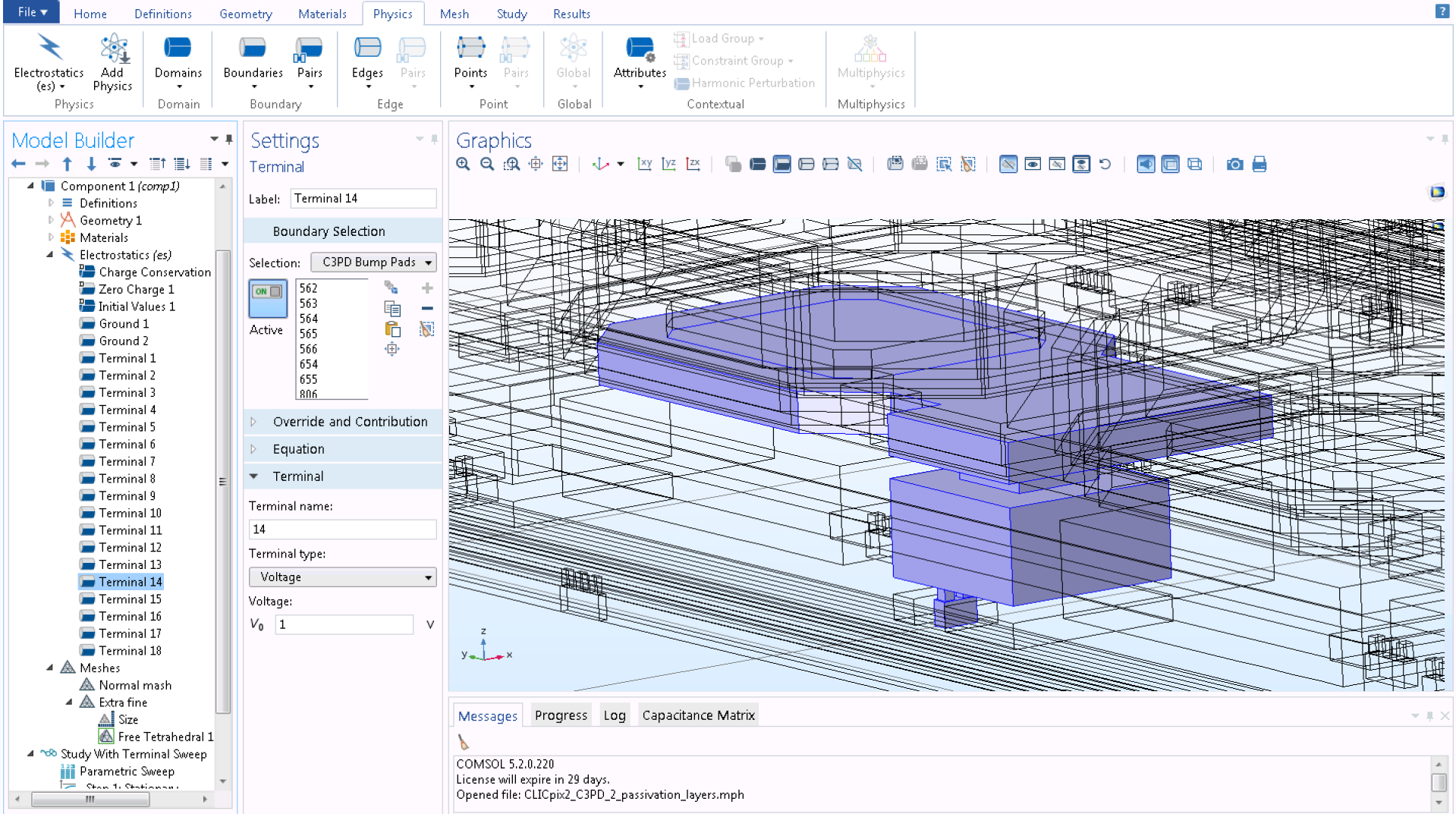
The **Messages** panel at the bottom shows:

- Progress: Log
- Capacitance Matrix
- COMSOL 5.2.0.220
- License will expire in 29 days.
- Opened file: CLICpix2_C3PD_2_passivation_layers.mph

Simulation

COMSOL Multiphysics[®] - Terminals

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The screenshot displays the COMSOL Multiphysics software interface. The top menu bar includes File, Home, Definitions, Geometry, Materials, Physics, Mesh, Study, and Results. The Physics toolbar shows various options like Electrostatics (es), Add Physics, Domains, Boundaries, Pairs, Edges, Points, Global, Attributes, Load Group, Constraint Group, and Multiphysics.

The **Model Builder** window on the left shows a tree view for Component 1 (comp1), including Definitions, Geometry 1, Materials, and Electrostatics (es). Under Electrostatics (es), there are sub-items like Charge Conservation, Zero Charge 1, Initial Values 1, Ground 1, Ground 2, and Terminals 1 through 18. Terminal 14 is currently selected.

The **Settings** window for Terminal 14 is open, showing the following configuration:

- Label: Terminal 14
- Boundary Selection: Selection: C3PD Bump Pads
- Active: A list of IDs (562, 563, 564, 565, 566, 654, 655, 806) with checkboxes, where 565 is checked.
- Terminal name: 14
- Terminal type: Voltage
- Voltage: $V_0 = 1$ V

The **Graphics** window on the right shows a 3D wireframe model of a complex structure with several blue-shaded rectangular regions representing the terminals. A coordinate system (x, y, z) is visible at the bottom left of the graphics area.

The **Messages** window at the bottom shows the following text:

```

COMSOL 5.2.0.220
License will expire in 29 days.
Opened file: CLICpix2_C3PD_2_passivation_layers.mph
    
```

Results

Capacitance Matrix

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COMSOL path: Results → Derived Values → Global Matrix Evaluation → Electrostatics → Terminals → Capacitance

Table 10 Progress Log

8.95 8.5 850 0.85

Capacitance (fF)

16.886	-0.39750	-1.5686E-8	-0.0014967	-5.7629E-5	-2.0997E-9	-4.2845E-10	-1.0636E-10	-7.7491E-13	-2.6928	-0.014929	-9.7037E-8	-0.0025388	-6.8890E-5	-1.2688E-8	-2.7128E-8	-4.9638E-9	-3.4026E-11
-0.39750	17.667	-0.39743	-5.7600E-5	-0.0014657	-5.7607E-5	-6.2144E-11	-3.5882E-10	-1.0650E-10	-0.016202	-2.6776	-0.014920	-3.2961E-5	-0.0024986	-6.8794E-5	-3.5494E-9	-2.3491E-8	-4.9723E-9
-1.5686E-8	-0.39743	17.327	-2.0964E-9	-5.7615E-5	-0.0015754	-4.5234E-13	-6.1819E-11	-4.4904E-10	-1.0170E-7	-0.016198	-2.6927	-9.3946E-9	-3.2873E-5	-0.0025520	-2.4359E-11	-3.5197E-9	-2.8074E-8
-0.0014967	-5.7600E-5	-2.0965E-9	16.887	-0.39736	-1.2395E-8	-0.0024343	-1.5725E-4	-3.3025E-9	-0.0025387	-6.8857E-5	-1.2669E-8	-2.6898	-0.014880	-8.5992E-8	-0.0030361	-5.0761E-5	-1.0888E-8
-5.7630E-5	-0.0014657	-5.7616E-5	-0.39736	17.667	-0.39730	-1.5718E-4	-0.0022368	-1.5725E-4	-3.2963E-5	-0.0024987	-6.8847E-5	-0.016120	-2.6746	-0.014876	-8.2951E-5	-0.0029634	-5.0759E-5
-2.0996E-9	-5.7607E-5	-0.0015754	-1.2395E-8	-0.39730	17.329	-3.3007E-9	-1.5728E-4	-0.0023546	-9.4453E-9	-3.2961E-5	-0.0025536	-8.7869E-8	-0.016122	-2.6898	-1.4377E-8	-8.3040E-5	-0.0030222
-4.2847E-10	-6.2143E-11	-4.5311E-13	-0.0024343	-1.5718E-4	-3.3008E-9	16.881	-0.39729	-1.4502E-8	-3.3869E-8	-4.9689E-9	-3.1233E-11	-0.0030362	-5.0752E-5	-1.0896E-8	-2.6923	-0.014942	-9.8739E-8
-1.0637E-10	-3.5882E-10	-6.1818E-11	-1.5725E-4	-0.0022367	-1.5728E-4	-0.39729	17.665	-0.39736	-5.4210E-9	-2.8627E-8	-4.9704E-9	-8.2976E-5	-0.0029644	-5.0760E-5	-0.016151	-2.6769	-0.014938
-7.7481E-13	-1.0650E-10	-4.4904E-10	-3.3025E-9	-1.5725E-4	-0.0023547	-1.4502E-8	-0.39736	17.328	-3.8498E-11	-5.4247E-9	-3.3749E-8	-1.4350E-8	-8.3054E-5	-0.0030232	-9.7434E-8	-0.016157	-2.6923
-2.6928	-0.016202	-1.0169E-7	-0.0025386	-3.2962E-5	-9.4447E-9	-3.3868E-8	-5.4207E-9	-3.8488E-11	7.0207	-0.030083	-2.9487E-6	-0.033500	-6.8671E-4	-3.6036E-7	-2.9691E-6	-3.6108E-7	-1.5354E-9
-0.014929	-2.6776	-0.016198	-6.8857E-5	-0.0024986	-3.2961E-5	-4.9687E-9	-2.8627E-8	-5.4247E-9	-0.030083	7.0506	-0.030060	-6.8650E-4	-0.032827	-6.8641E-4	-3.6184E-7	-2.6066E-6	-3.6166E-7
-9.7041E-8	-0.014920	-2.6927	-1.2670E-8	-6.8845E-5	-0.0025535	-3.1196E-11	-4.9703E-9	-3.3749E-8	-2.9487E-6	-0.030061	6.9887	-3.6012E-7	-6.8610E-4	-0.033467	-1.5370E-9	-3.6180E-7	-2.9708E-6
-0.0025387	-3.2961E-5	-9.3938E-9	-2.6898	-0.016120	-8.7866E-8	-0.0030362	-8.2977E-5	-1.4350E-8	-0.033500	-6.8650E-4	-3.6010E-7	7.0538	-0.029399	-2.5881E-6	-0.033180	-6.8078E-4	-3.5927E-7
-6.8890E-5	-0.0024987	-3.2873E-5	-0.014880	-2.6746	-0.016122	-5.0752E-5	-0.0029644	-8.3054E-5	-6.8671E-4	-0.032827	-6.8610E-4	-0.029399	7.0835	-0.029376	-6.8142E-4	-0.032472	-6.8087E-4
-1.2689E-8	-6.8793E-5	-0.0025521	-8.5996E-8	-0.014876	-2.6898	-1.0897E-8	-5.0760E-5	-0.0030231	-3.6036E-7	-6.8641E-4	-0.033467	-2.5881E-6	-0.029376	7.0533	-3.5956E-7	-6.8097E-4	-0.033181
-2.7129E-8	-3.5492E-9	-2.4360E-11	-0.0030360	-8.2949E-5	-1.4376E-8	-2.6923	-0.016151	-9.7434E-8	-2.9692E-6	-3.6183E-7	-1.5373E-9	-0.033180	-6.8142E-4	-3.5954E-7	7.0201	-0.030088	-2.9502E-6
-4.9640E-9	-2.3491E-8	-3.5195E-9	-5.0761E-5	-0.0029632	-8.3040E-5	-0.014942	-2.6769	-0.016157	-3.6109E-7	-2.6066E-6	-3.6180E-7	-6.8079E-4	-0.032472	-6.8096E-4	-0.030088	7.0499	-0.030073
-3.4016E-11	-4.9721E-9	-2.8072E-8	-1.0888E-8	-5.0758E-5	-0.0030223	-9.8737E-8	-0.014938	-2.6923	-1.5355E-9	-3.6165E-7	-2.9707E-6	-3.5927E-7	-6.8087E-4	-0.033181	-2.9502E-6	-0.030073	7.0196

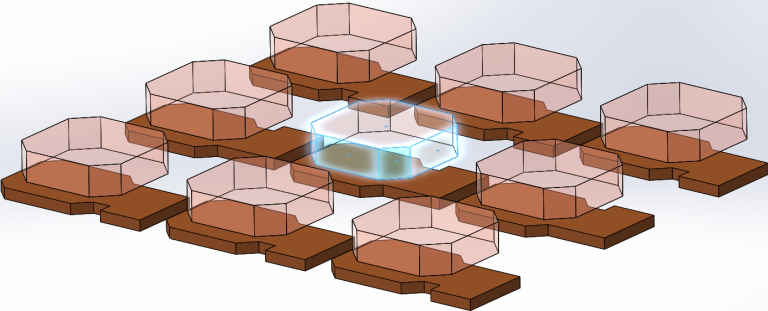
Results

Capacitance Matrix

COMSOL path: Results → Derived Values → Global Matrix Evaluation → Electrostatics → Terminals → Capacitance

Table 10 Progress Log

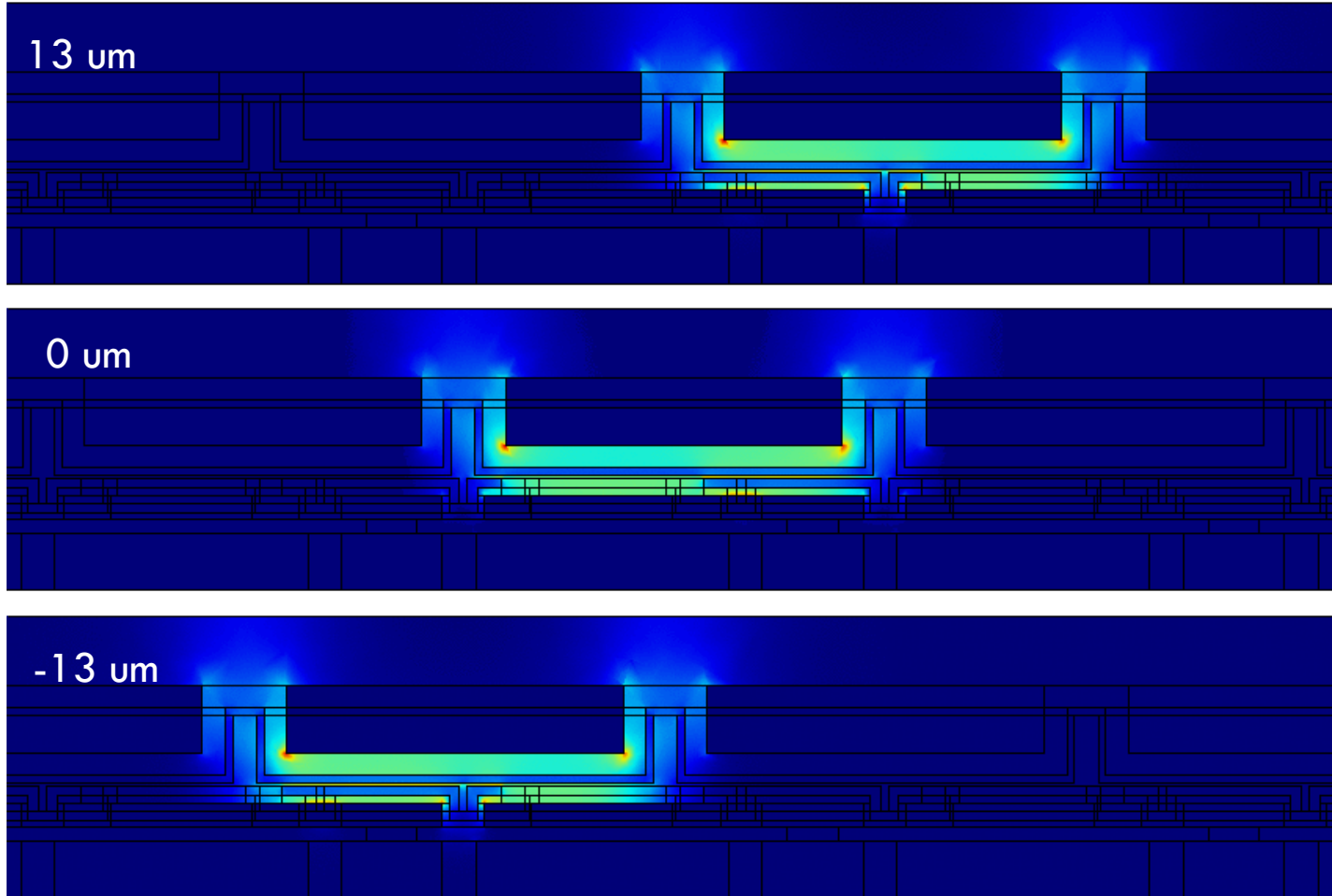
Terminal 14 = Middle C3PD pixel



Capacitance (fF)																	
16.886	-0.39750	-1.5686E-8	-0.0014967	-5.7629E-5	-2.0997E-9	-4.2845E-10	-1.0636E-10	-7.7491E-13	-2.6928	-0.014929	-9.7037E-8	-0.0025388	-6.8890E-5	-1.2688E-8	-2.7128E-8	-4.9638E-9	-3.4026E-11
-0.39750	17.667	-0.39743	-5.7600E-5	-0.0014657	-5.7607E-5	-6.2144E-11	-3.5882E-10	-1.0650E-10	-0.016202	-2.6776	-0.014920	-3.2961E-5	-0.0024986	-6.8794E-5	-3.5494E-9	-2.3491E-8	-4.9723E-9
-1.5686E-8	-0.39743									-0.016198	-2.6927	-9.3946E-9	-3.2873E-5	-0.0025520	-2.4359E-11	-3.5197E-9	-2.8074E-8
-0.0014967	-5.7600E-5									-6.8857E-5	-1.2669E-8	-2.6898	-0.014880	-8.5992E-8	-0.0030361	-5.0761E-5	-1.0888E-8
-5.7630E-5	-0.0014657									-0.0024987	-6.8847E-5	-0.016120	-2.6746	-0.014876	-8.2951E-5	-0.0029634	-5.0759E-5
-2.0996E-9	-5.7607E-5									-3.2961E-5	-0.0025536	-8.7869E-8	-0.016122	-2.6898	-1.4377E-8	-8.3040E-5	-0.0030222
-4.2847E-10	-6.2143E-11									-4.9689E-9	-3.1233E-11	-0.0030362	-5.0752E-5	-1.0896E-8	-2.6923	-0.014942	-9.8739E-8
-1.0637E-10	-3.5882E-11									-2.8627E-8	-4.9704E-9	-8.2976E-5	-0.0029644	-5.0760E-5	-0.016151	-2.6769	-0.014938
-7.7481E-13	-1.0650E-11									-5.4247E-9	-3.3749E-8	-1.4350E-8	-8.3054E-5	-0.0030232	-9.7434E-8	-0.016157	-2.6923
-2.6928	-0.016202									-0.030083	-2.9487E-6	-0.033500	-6.8671E-4	-3.6036E-7	-2.9691E-6	-3.6108E-7	-1.5354E-9
-0.014929	-2.6776									7.0506	-0.030060	-6.8650E-4	-0.032827	-6.8641E-4	-3.6184E-7	-2.6066E-6	-3.6166E-7
-9.7041E-8	-0.014920									-0.030061	6.9887	-3.6012E-7	-6.8610E-4	-0.033467	-1.5370E-9	-3.6180E-7	-2.9708E-6
-0.0025387	-3.2961E-5									-6.8650E-4	-3.6010E-7	7.0538	-0.029399	-2.5881E-6	-0.033180	-6.8078E-4	-3.5927E-7
-6.8890E-5	-0.0024987									-0.032827	-6.8610E-4	-0.029399	7.0835	-0.029376	-6.8142E-4	-0.032472	-6.8087E-4
-1.2689E-8	-6.8793E-5									-6.8641E-4	-0.033467	-2.5881E-6	-0.029376	7.0533	-3.5956E-7	-6.8097E-4	-0.033181
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-4.9640E-9	-2.3491E-8	-3.5195E-9	-5.0761E-5	-0.0029632	-8.3040E-5	-0.014942	-2.6769	-0.016157	-3.6109E-7	-2.6066E-6	-3.6180E-7	-6.8079E-4	-0.032472	-6.8096E-4	-0.030088	7.0499	-0.030073
-3.4016E-11	-4.9721E-9	-2.8072E-8	-1.0888E-8	-5.0758E-5	-0.0030223	-9.8737E-8	-0.014938	-2.6923	-1.5355E-9	-3.6165E-7	-2.9707E-6	-3.5927E-7	-6.8087E-4	-0.033181	-2.9502E-6	-0.030073	7.0196

Misalignment Scan (Via direction)

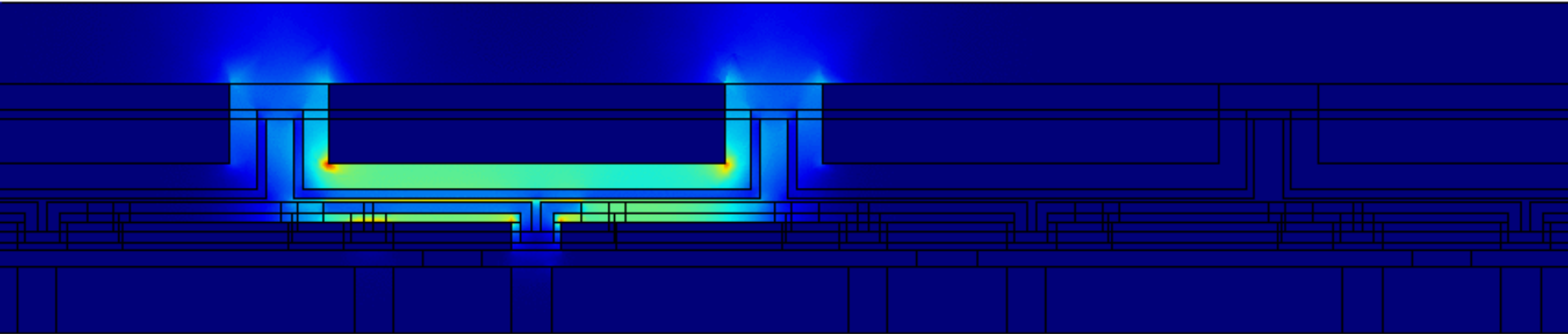
Electric field norm between pixels



CCPDv3 shifting from -13 to 13 um away from ideal alignment.
Color scale shows the electric field norm.

Misalignment Scan (Via direction)

Electric field norm between pixels



Animated GIF - CCPDv3 shifting from -13 to 13 μm away from ideal alignment.
Color scale shows the electric field norm.