Studies of Potential in CCDs – Introduction

- Start from Maxwell's equation which relates electric field to charge density:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon \varepsilon_0}.$$

- The field is given by the potential:

$$\vec{E} = -\nabla V.$$

- Together, these give Poisson's equation which we must solve to determine the potential in a (fully depleted) CCD:

$$\nabla^2 V = -\frac{\rho}{\varepsilon \varepsilon_0}.$$

- Using the Taylor expansion:

$$V(x_i + h) \approx V_i + \frac{\partial V_i}{\partial x} + \frac{h^2}{2}\frac{\partial^2 V_i}{\partial x^2},$$

$$V(x_i - h) \approx V_i - \frac{\partial V_i}{\partial x} + \frac{h^2}{2}\frac{\partial^2 V_i}{\partial x^2}.$$

- Adding these gives:

$$V_{i+1} + V_{i-i} \approx 2V_i + h^2 \frac{\partial^2 V_0}{\partial x^2}.$$

- Hence

$$\frac{\partial^2 V_i}{\partial x^2} = \frac{1}{h^2}\left(V_{i-1} + V_{i+1} - 2V_i\right)$$

- Extending to 2D

$$\nabla^2 V_{i,j} = \frac{1}{{h_x}^2}\left(V_{i-1,j} + V_{i+1,j} - 2V_{i,j}\right) + \frac{1}{{h_y}^2}\left(V_{i,j-1} + V_{i,j+1} - 2V_{i,j}\right).$$

Introduction

- Substitute in Poisson's equation:

$$\frac{1}{h_x^{\,2}}\left(V_{i-1,j}+V_{i+1,j}-2V_{i,j}\right)$$

$$+\frac{1}{h_y^{\,2}}\left(V_{i,j-1}+V_{i,j+1}-2V_{i,j}\right)=\frac{-\rho_{i,j}}{\varepsilon_{i,j}\,\varepsilon_0}.$$

- Rewrite:

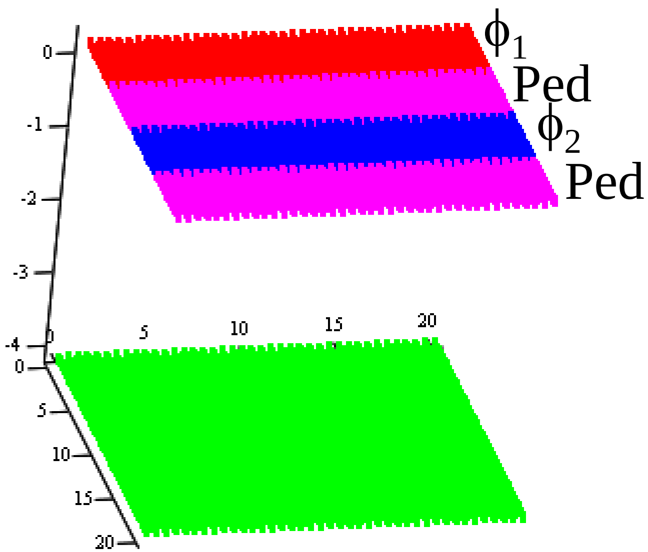
$$V'_{i,j}=\frac{h_x^{\,2}h_y^{\,2}}{2(h_x^{\,2}+h_y^{\,2})}\times\left(\frac{V_{i-1,j}+V_{i+1,j}}{h_x^{\,2}}+\frac{V_{i,j-1}+V_{i,j+1}}{h_y^{\,2}}+\frac{\rho_{i.j}}{\varepsilon_{i,j}\,\varepsilon_0}\right).$$

- Use this to solve iteratively for V.
- "Tortoise convergence" i.e. sure, but slow!
- Choosing reasonable initial guess at potential speeds up solution.
- Need only calculate potential in one pixel if use periodic boundary conditions, e.g.

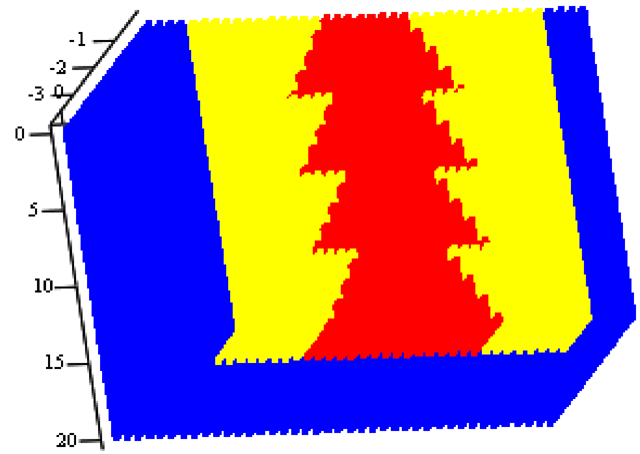
$$V'_{0,j}=\frac{h_x^{\,2}h_y^{\,2}}{2(h_x^{\,2}+h_y^{\,2})}\times\left(\frac{V_{N_x,j}+V_{1,j}}{h_x^{\,2}}+\frac{V_{0,j-1}+V_{0,j+1}}{h_y^{\,2}}+\frac{\rho_{i,j}}{\varepsilon_{i,j}\,\varepsilon_0}\right).$$

Potential in Christmas Tree CCD

- Gate structure:



- Dopant concentrations.

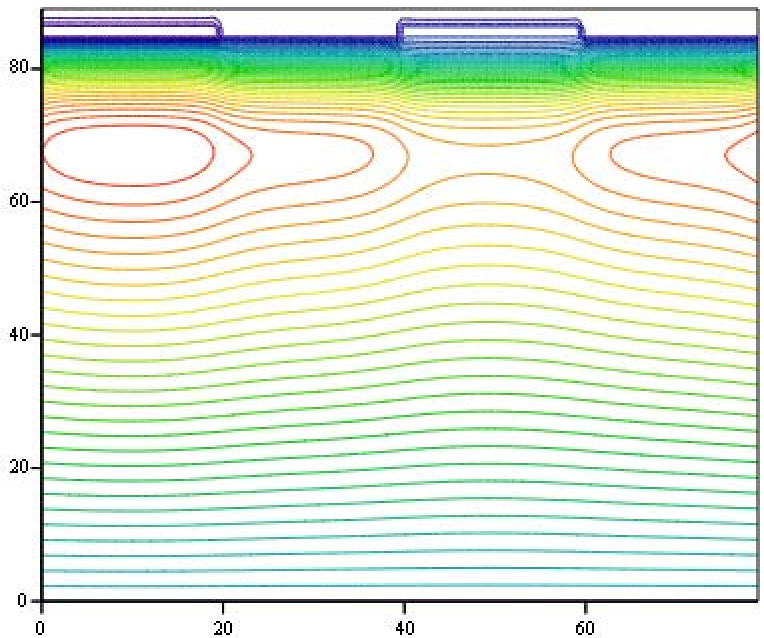


- Red, $3.0 \times 10^{22}\ m^{-3}$.
- Yellow, $1.5 \times 10^{22}\ m^{-3}$.
- Blue, $1 \times 10^{19}\ m^{-3}$.

CTCCD potential

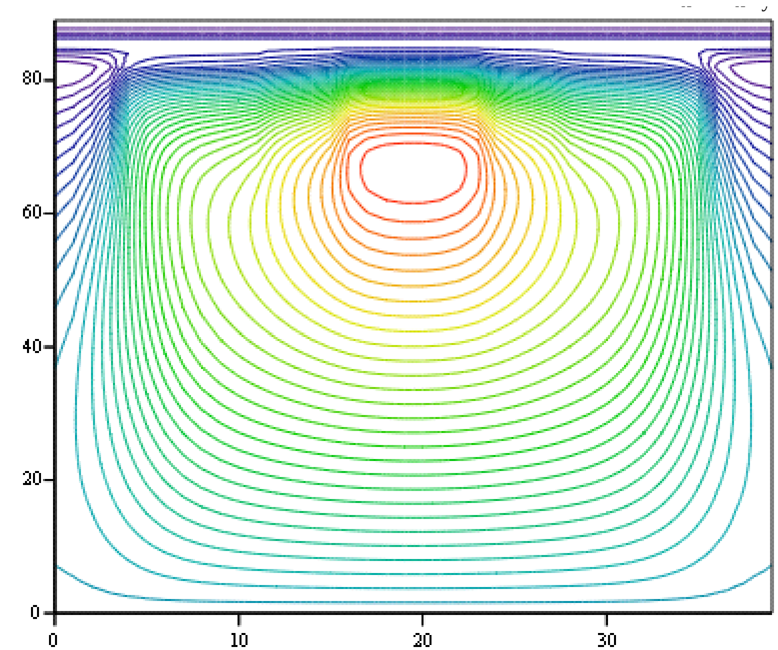
- Calculate potential with $V_1 = 2.0$ V, $V_2 = 0.0$ V, $V_{Ped} = (V_1 + V_2)/2$.
- Vertical section normal to gates through Christmas tree structure.

ϕ_1 Ped ϕ_2 Ped



Upfxy

- Vertical section along gate 1.

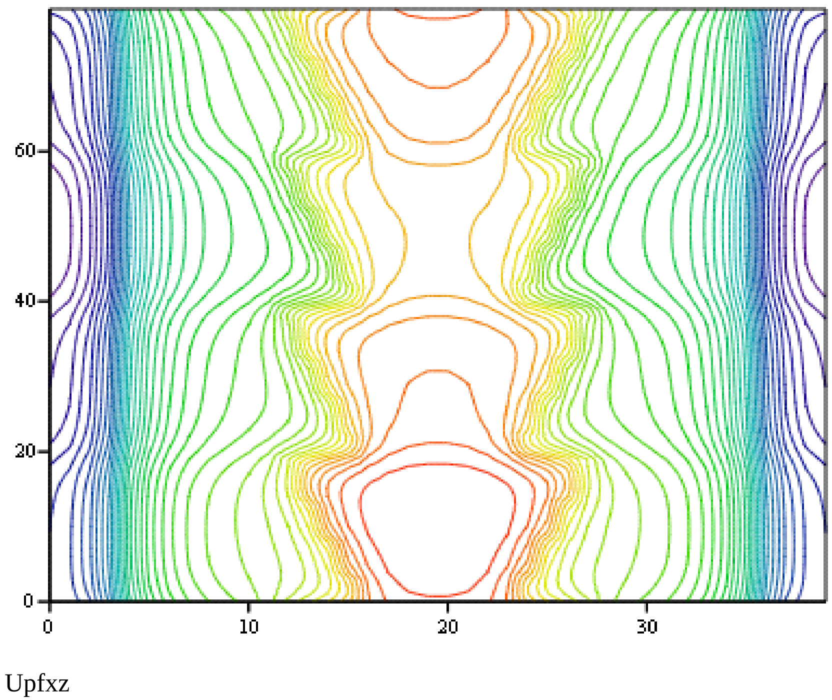


Upfyz

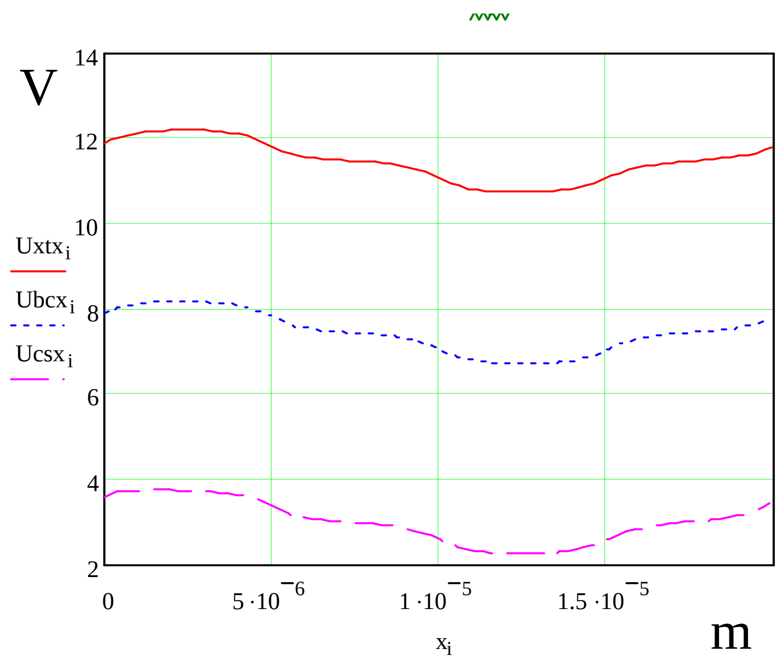
- (Units on axes of this and previous plot are number of grid points!)

CTCCD potential

- Horizontal section at depth of buried channel.

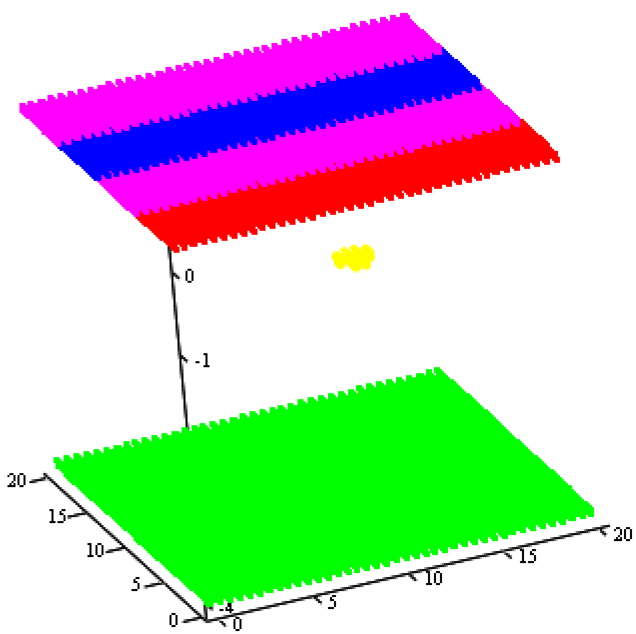


- Potential along Christmas tree, along buried channel next to Christmas tree and along channel stop (from top to bottom).



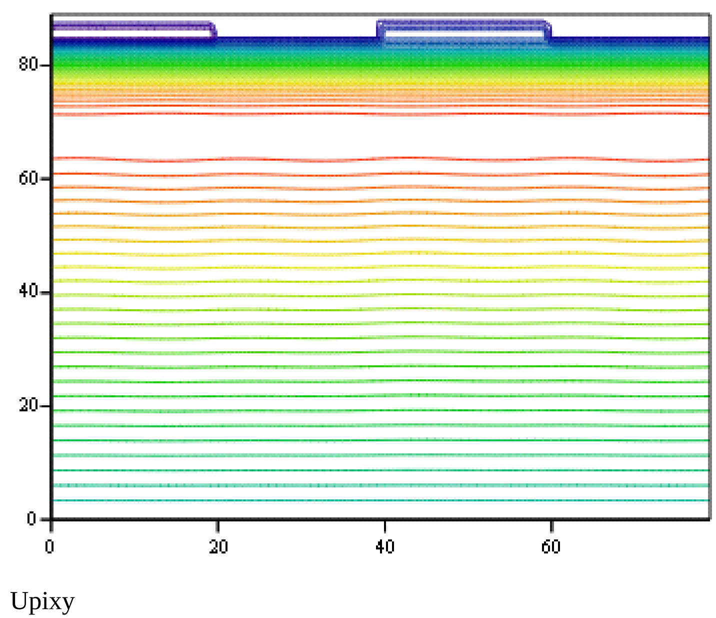
CTCCD potential

- Classically, the electrons are trapped where $q_e V > k_B T$, i.e. $V > k_B T/q_e$:



- (Here looking upwards through pixel at gates!)

- Scan of behaviour of potential close to point at which electrons shift from one gate to next may help to reveal any CTI problems.
- A start: vertical section through gates for $V_1 = 1.0$ V, $V_2 = 1.0$ V:



Capacitance calculations

- Extension of above should allow determinations of effective gate capacitance.
- Must determine charge that drive needs to supply in order to change gate voltage.
- Use Gauss' law...

$$\oint_{gate} \vec{E} \cdot d\vec{S} = \frac{Q_{gate}}{\varepsilon \varepsilon_0}$$

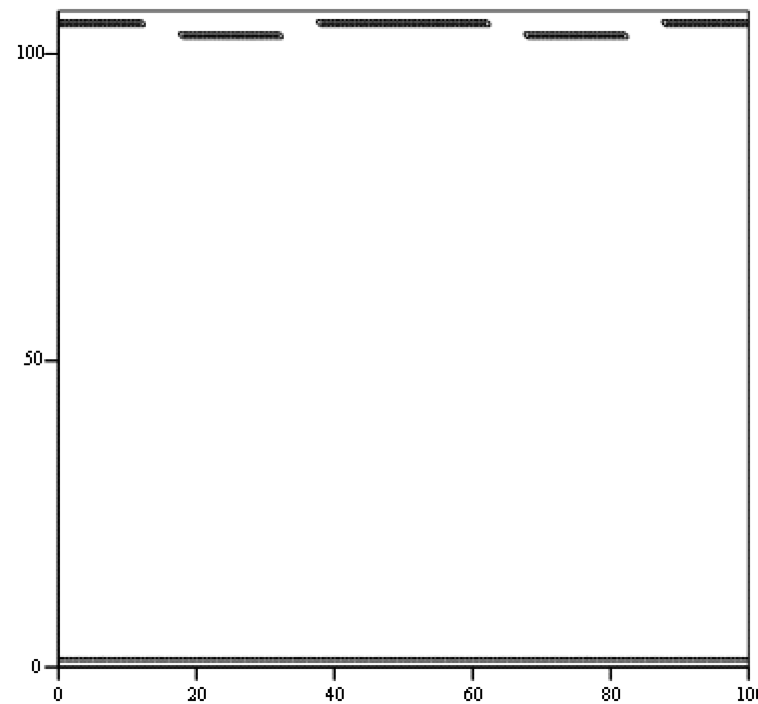
- ...for two different gate voltages, then calculate capacitance:

$$C = \frac{\Delta Q}{\Delta V}.$$

- Have made several mistakes in trying to do this: no sensible numbers yet...

Pedestal CCDs

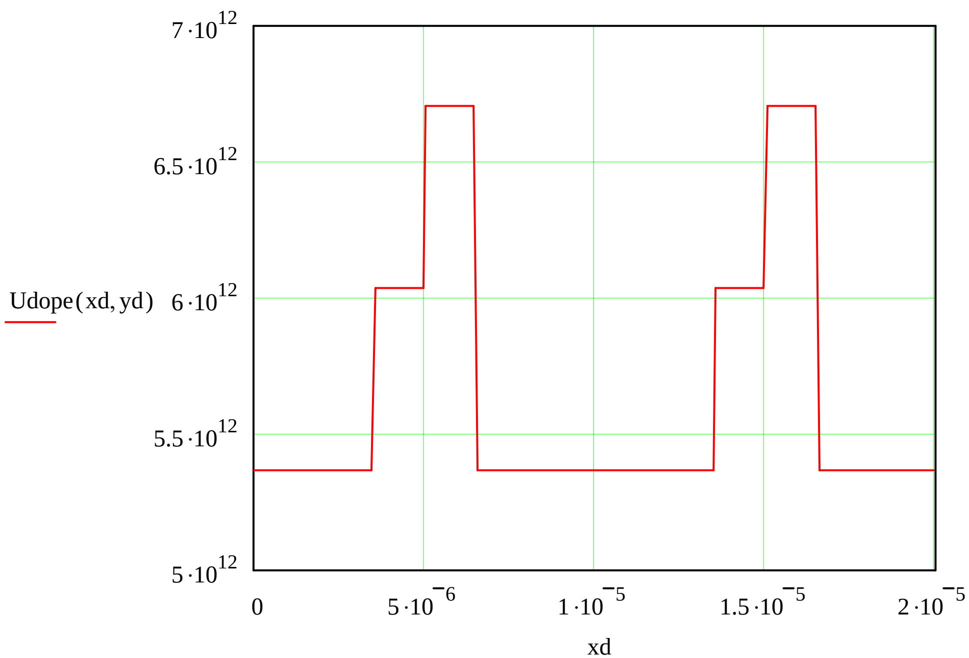
- Similar calculations done in 2D for "pedestal" CCD:



εCPC2

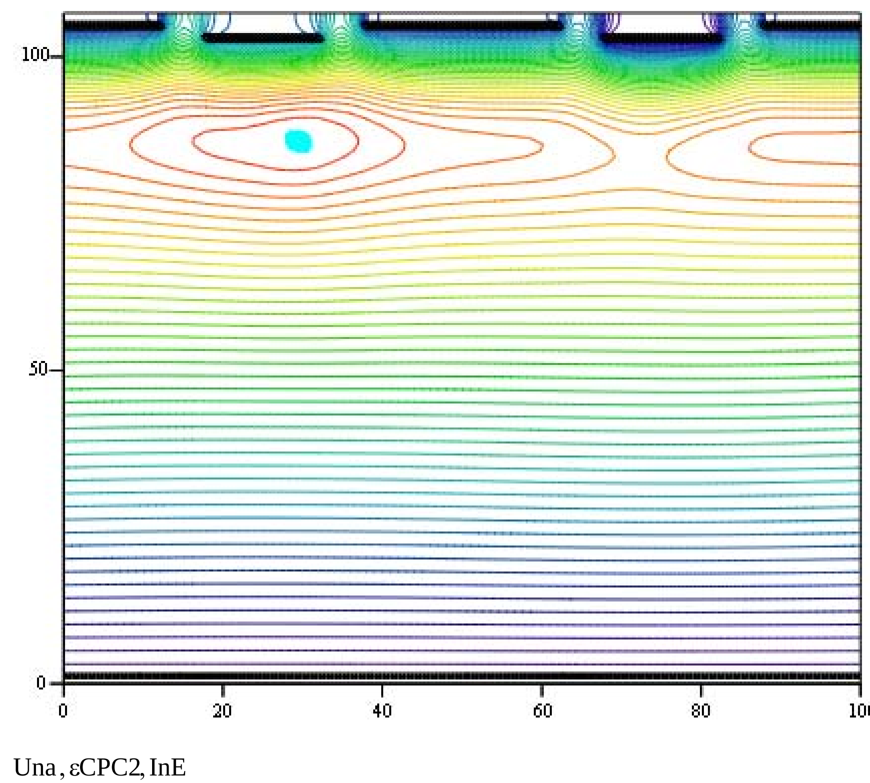
PCCD potential

- Dopant concentration under gates "stepped":



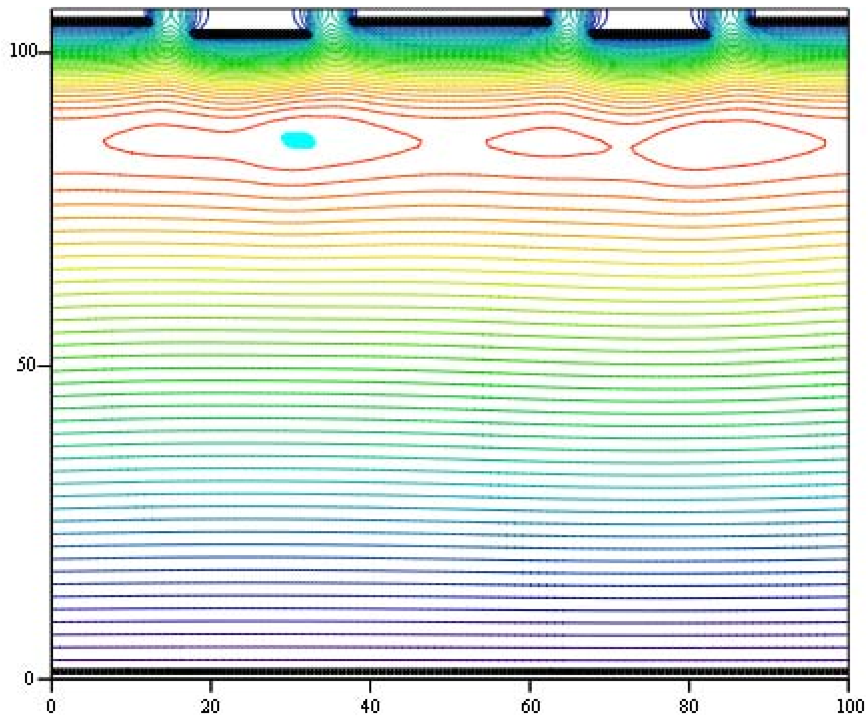
- ...but values chosen (10% variation of concentration from step to step) unrealistic.

- Nonetheless, this structure certainly looks promising.
- $V_1 = 2.0$ V, $V_2 = 0.0$ V:



PCCD potential

- $V_1 = 1.2$ V, $V_2 = 0.8$ V.



Una, εCPC2, InE

- This case illustrates possible CTI problems due to inter-gate gaps.

Summary

- Tools to study potential in CCDs being developed and (slowly) understood.
- Extension to capacitance calculations in progress.
- Investigation of novel CCD structures started.
- These look promising and are candidates for test structures that could be manufactures by e2v.
- Study these (and other ideas) further to try and maximise likelihood that test structures function well.