Radiation Hardness Studies in a CCD with High-Speed Column Parallel Readout

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On behalf of the LCFI Collaboration

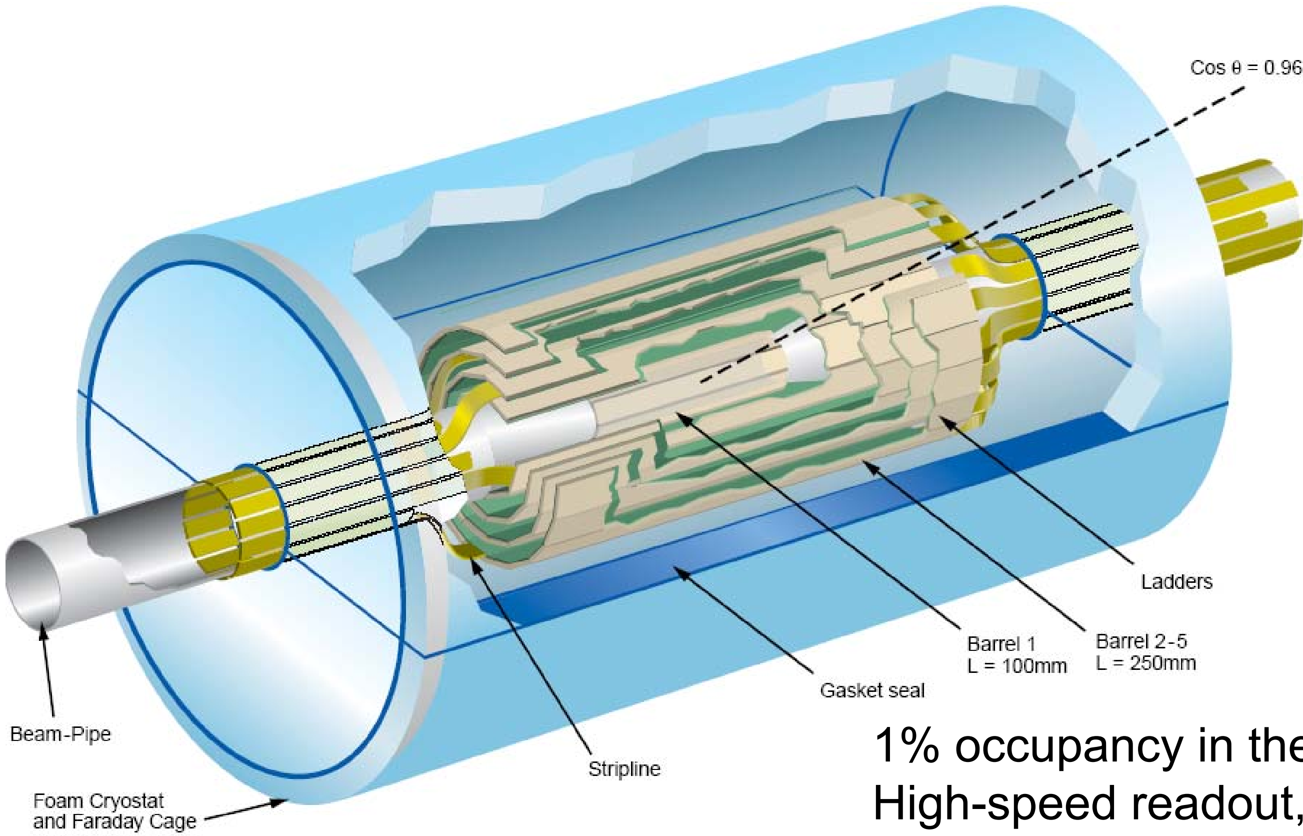
Outline

- ILC and CCD Vertex Detector
- Background rates and radiation damage
- Charge Transfer Inefficiency (CTI)
- TCAD simulation results
- Comparison with an analytical model
- Test-stand measurements in preparation
- Conclusions

International Linear Collider: Vertex Detector

LCFI: Linear Collider Flavour Identification collaboration

Vertex Detector will provide precise 3D space points along tracks.



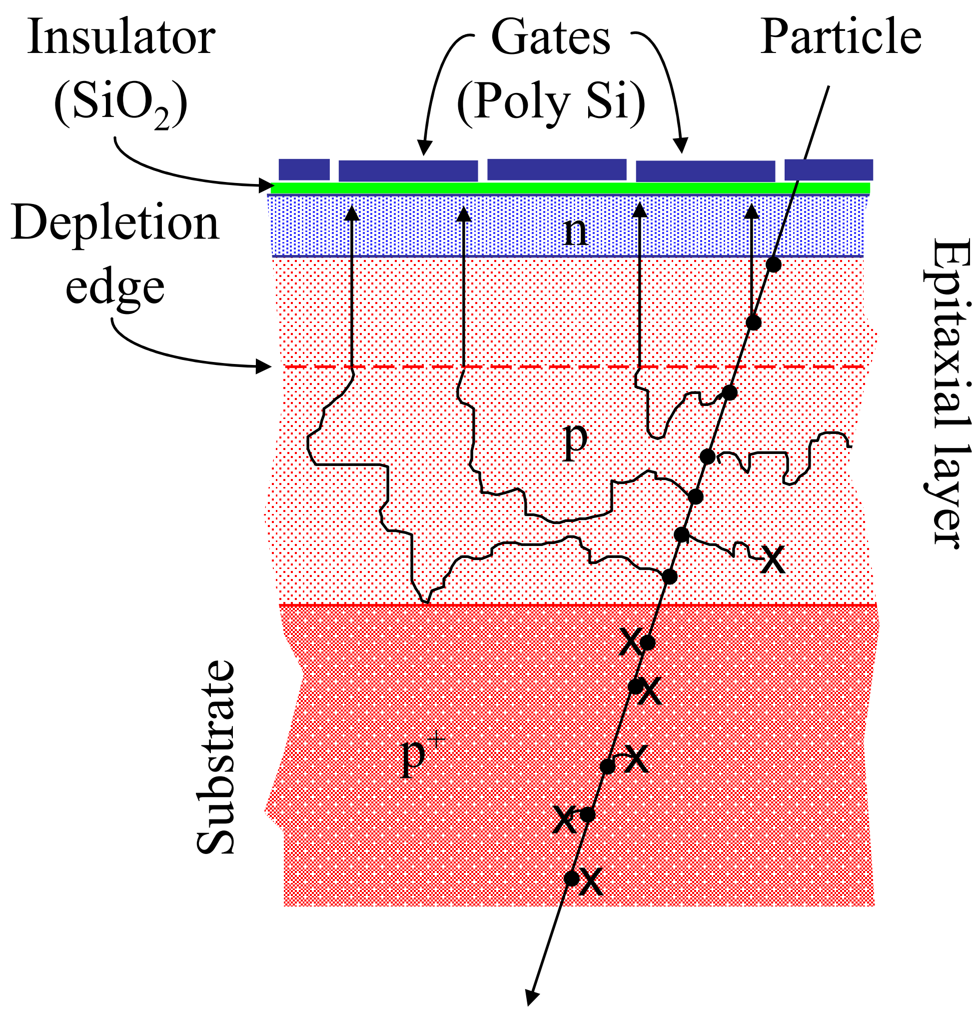
800M channels of $20\mu m \times 20\mu m$ pixels.

< 0.1% X_0 layer thickness to minimize multiple scattering. Inner radius 14mm.

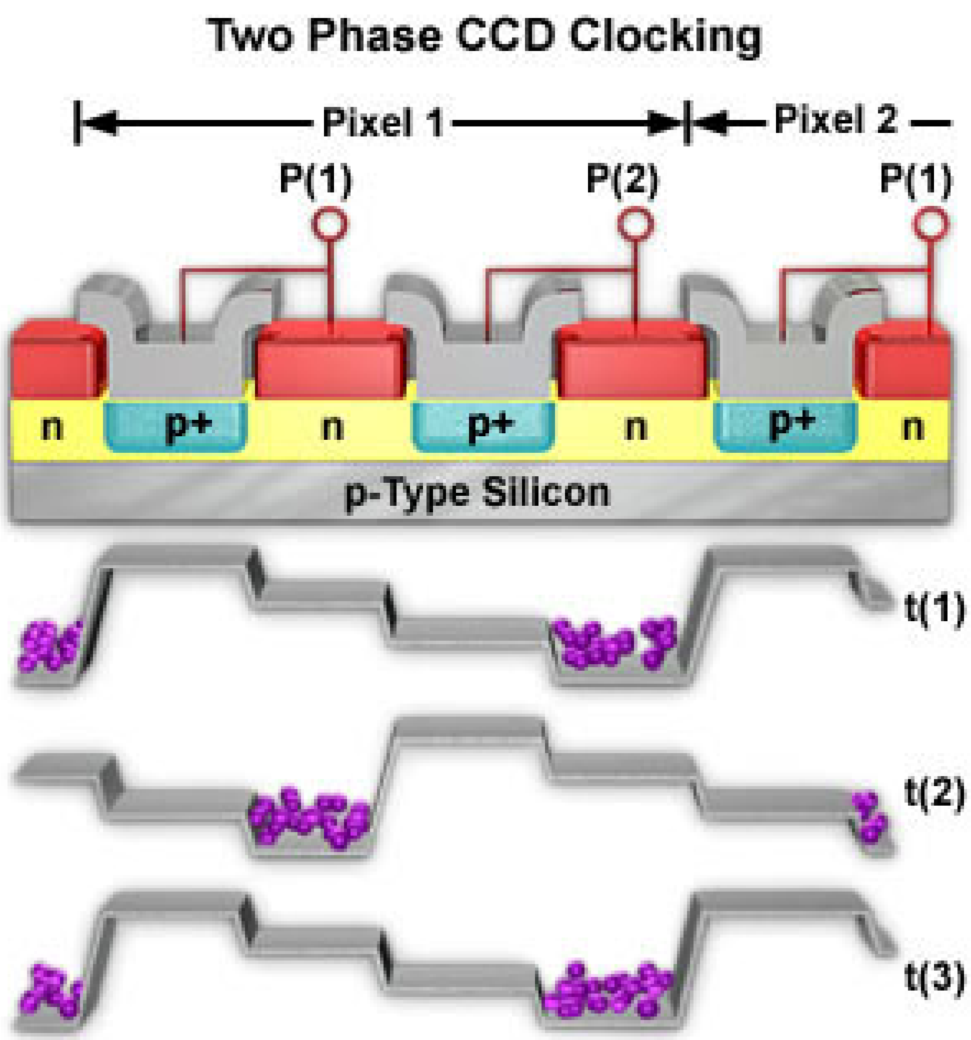
1% occupancy in the innermost layer.
High-speed readout, up to 50 MHz;
20 readouts during 1 ms bunch train.

Requires radiation hardness studies.

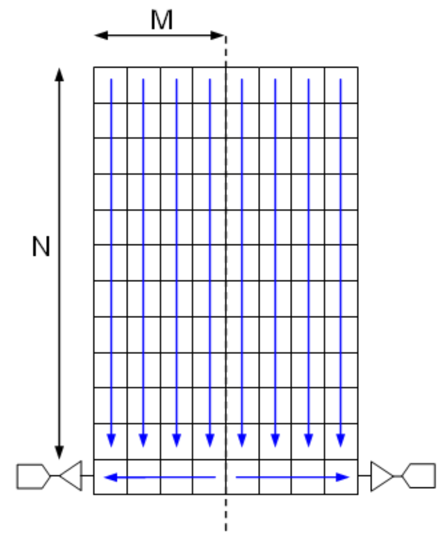
The CCD: Charge Collection



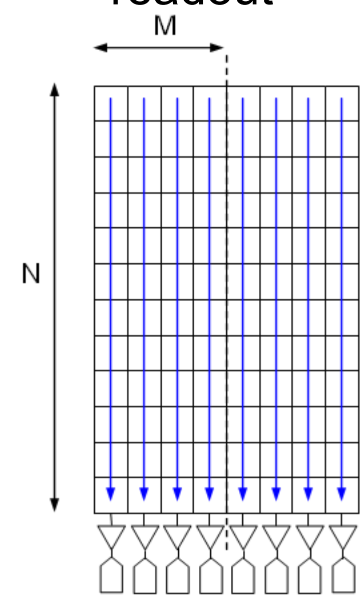
The CCD: Charge Transfer



classic readout



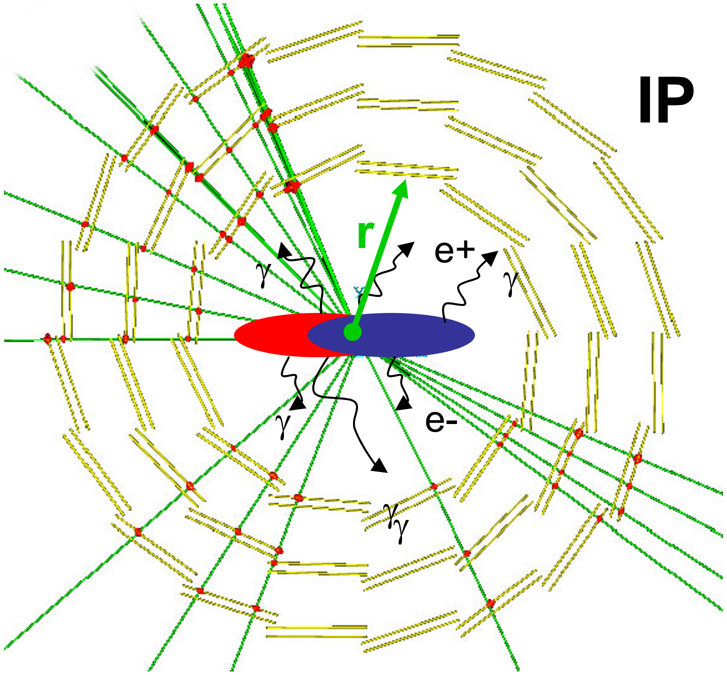
Column parallel (CP) readout



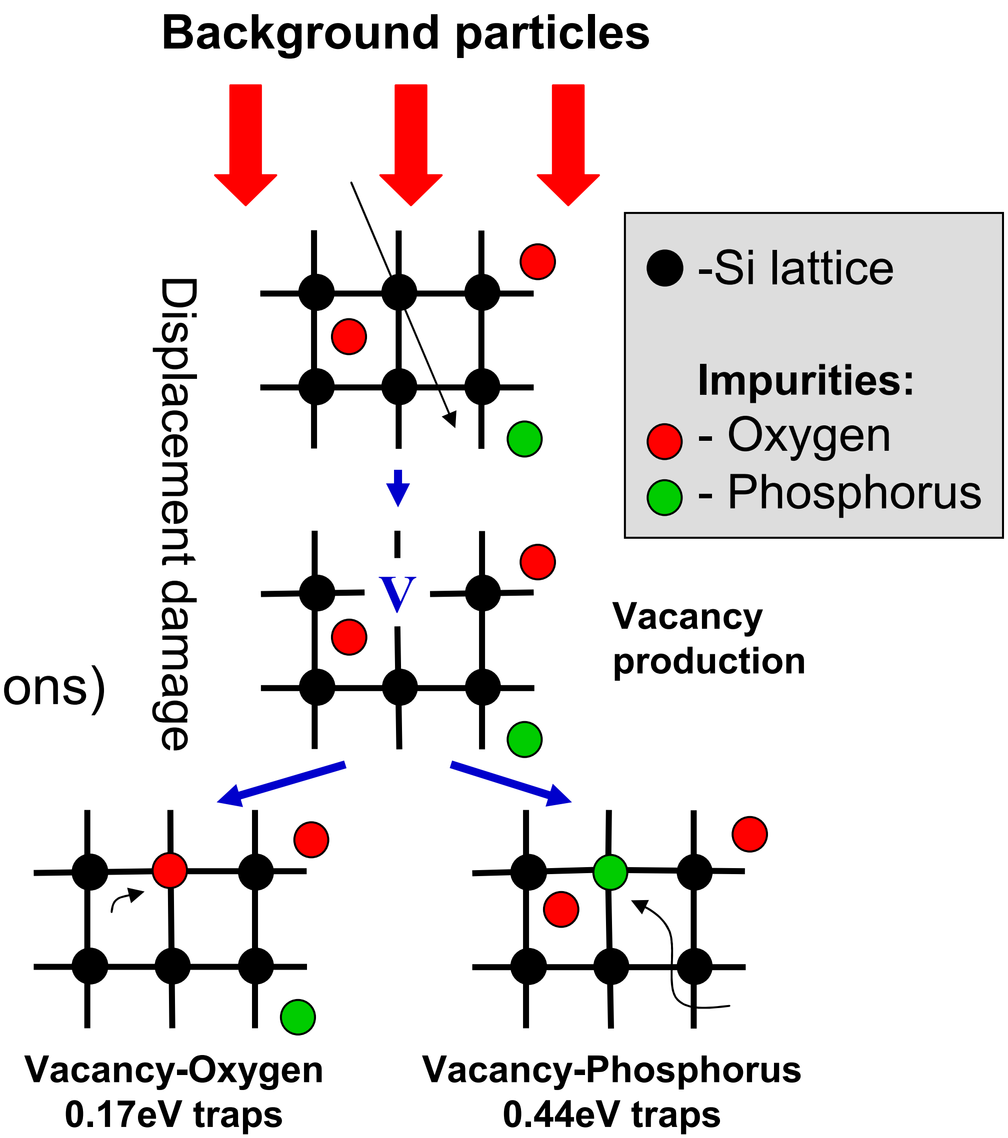
$$t_{serial} = \frac{N \bullet M}{f_{out}}$$

$$t_{CP-CCD} = \frac{N}{f_{out}}$$

ILC Background and CCD Radiation Damage



Background: e and n (from γ reactions)



Radiation damage produces energy levels **(traps)** within the band gap.

Traps capture electrons from the conduction band which are later released.

Estimation of Background Rates

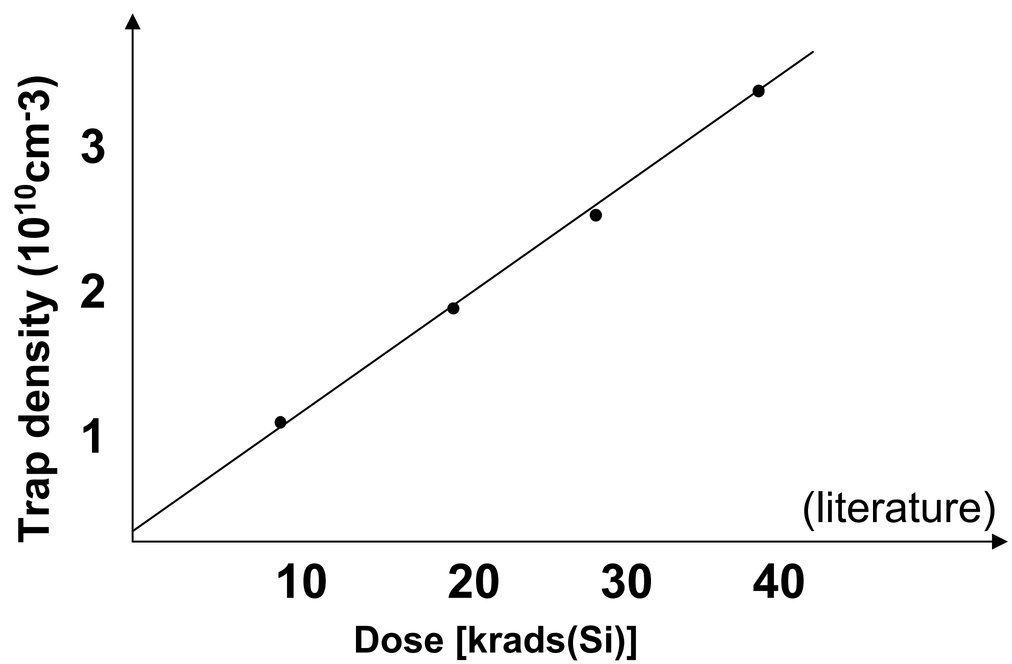
Simulator (e^+e^- **pairs**)	SiD	LDC	GLD
CAIN/Jupiter hits/cm²/bx	**2.9** **(nominal)**	**3.5** **(TESLA)**	**0.5** (24mm radius, nominal)
GuineaPig hits/cm²/bx	**2.3** **(nominal)**	**3.0** **(TESLA)**	**2.0** (20mm radius, nominal)

(bx: bunch crossing)

(T.Maruyama, C.Rimbault)

- 2820 bx/train
- 5 trains per second
- 10^7 seconds in the \`Snowmass year'

$1.41\cdot10^{11}$ bunches/year



Background and Trap Density

Expected background in the ILC at 14 mm radius for 1 year operation.

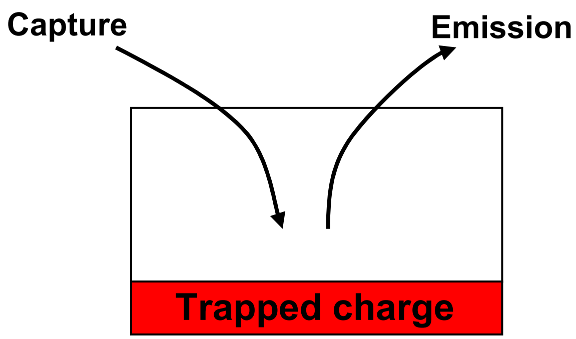
Parameter	electrons	neutrons
average energy	~ 10MeV	~ 1MeV
no. particles / bx / cm^2	3.5	0.01
fluence (annual dose)	$0.5 \cdot 10^{12}$	$1.6 \cdot 10^9$ Vogel $1 \cdot 10^9$ Maruyama

Estimated trap densities for simulation purpose.

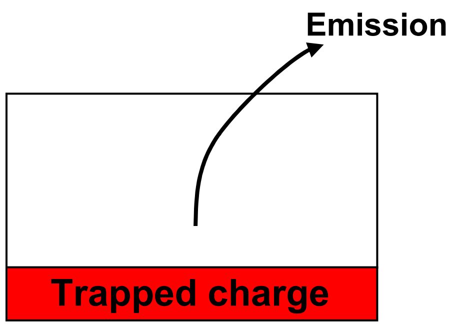
Source	- 0.17eV trap	- 0.44eV trap
electrons	$\sim 3 \cdot 10^{11}\ cm^{-3}$	$\sim 3 \cdot 10^{10}\ cm^{-3}$
neutrons	$\sim 7.1 \cdot 10^{8} cm^{-3}$ $\sim 4.5 \cdot 10^{8} cm^{-3}$	$\sim 1.1 \cdot 10^{10} cm^{-3}$ $\sim 7.0 \cdot 10^{9} cm^{-3}$
total	$\sim 3 \cdot 10^{11} cm^{-3}$	$\sim 4.1 \cdot 10^{10} cm^{-3}$ $\sim 3.7 \cdot 10^{10} cm^{-3}$
Used in simulations	$1 \cdot 10^{12} cm^{-3}$	$1 \cdot 10^{12} cm^{-3}$

Simulation: about 3 or many more years of operation.

CTI Modeling - Principle



During transfer



After transfer

- Traps capture electrons from the signal charge.
- Electrons are emitted later:

capture τ_c and emission τ_e time constants.

$$\tau_c = \frac{1}{\sigma_n v_{th} n_s}$$

(~ ns)

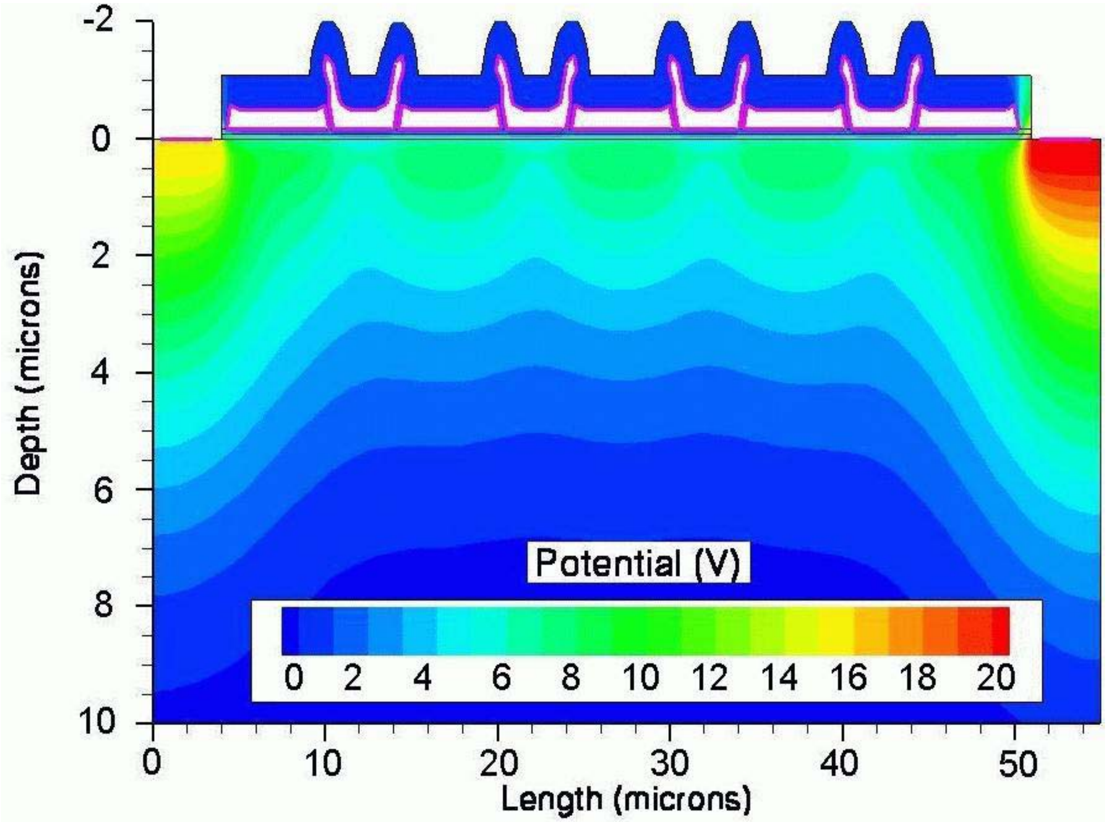
$$\tau_e = \frac{1}{\sigma_n x_n v_{th} N_c} \exp\left(\frac{E_c - E_t}{kT}\right)$$

Strongly dependent on temperature and trap energy level (seconds to ns)

CCD Simulations in ISE-TCAD

ISE-TCAD package (version 7.5) - **DESSIS** program (**D**evice **S**imulation for **S**mart **I**ntegrated **S**ystems).
Simplified 2D model containing only one pixel of CCD structure.

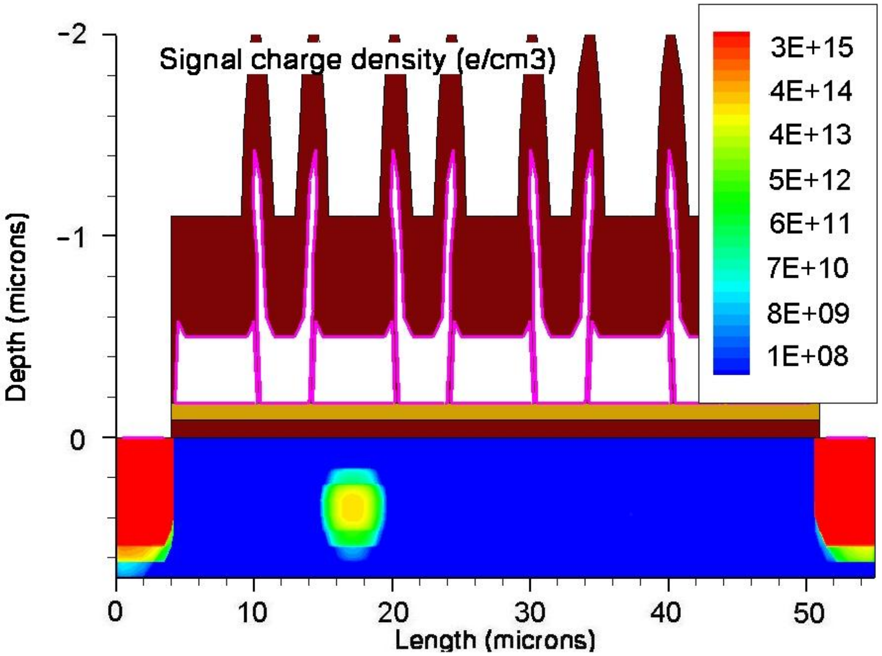
| one pixel |



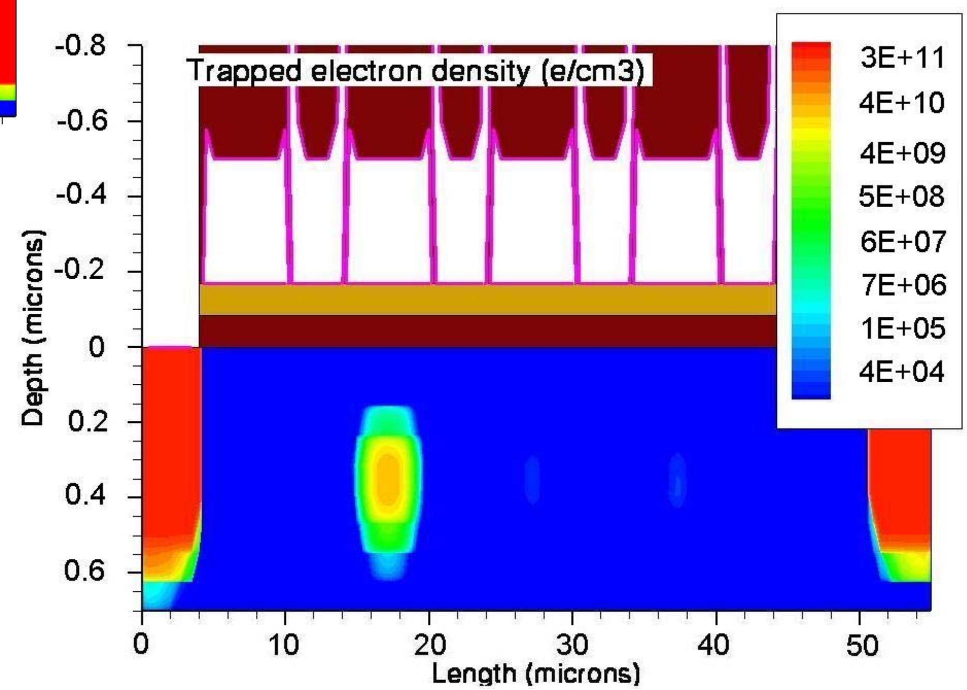
Epitaxial layer is doped with boron (p-type)

additional doping profiles: substrate, p+ implants, input gate, and output gate. The contact nodes for the pixels are poly-silicon with silicon nitride and silicon oxide. layers beneath them.

CTI Definition and Modelling in TCAD



CTI – the ratio of the charge lost in the transfer from pixel n to pixel n+1 to the charge entering pixel n.



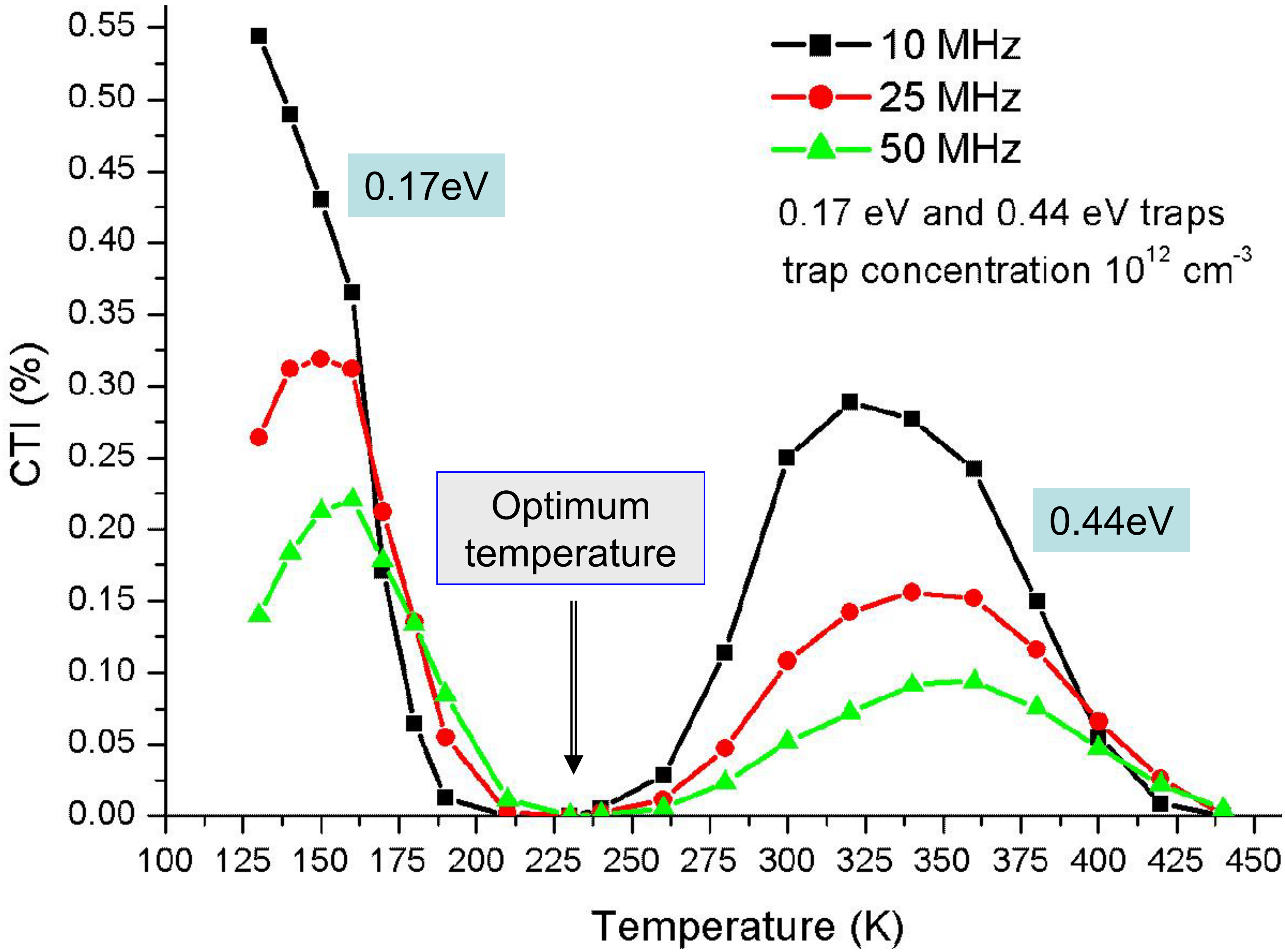
Simulations

Parameters of CTI simulations:

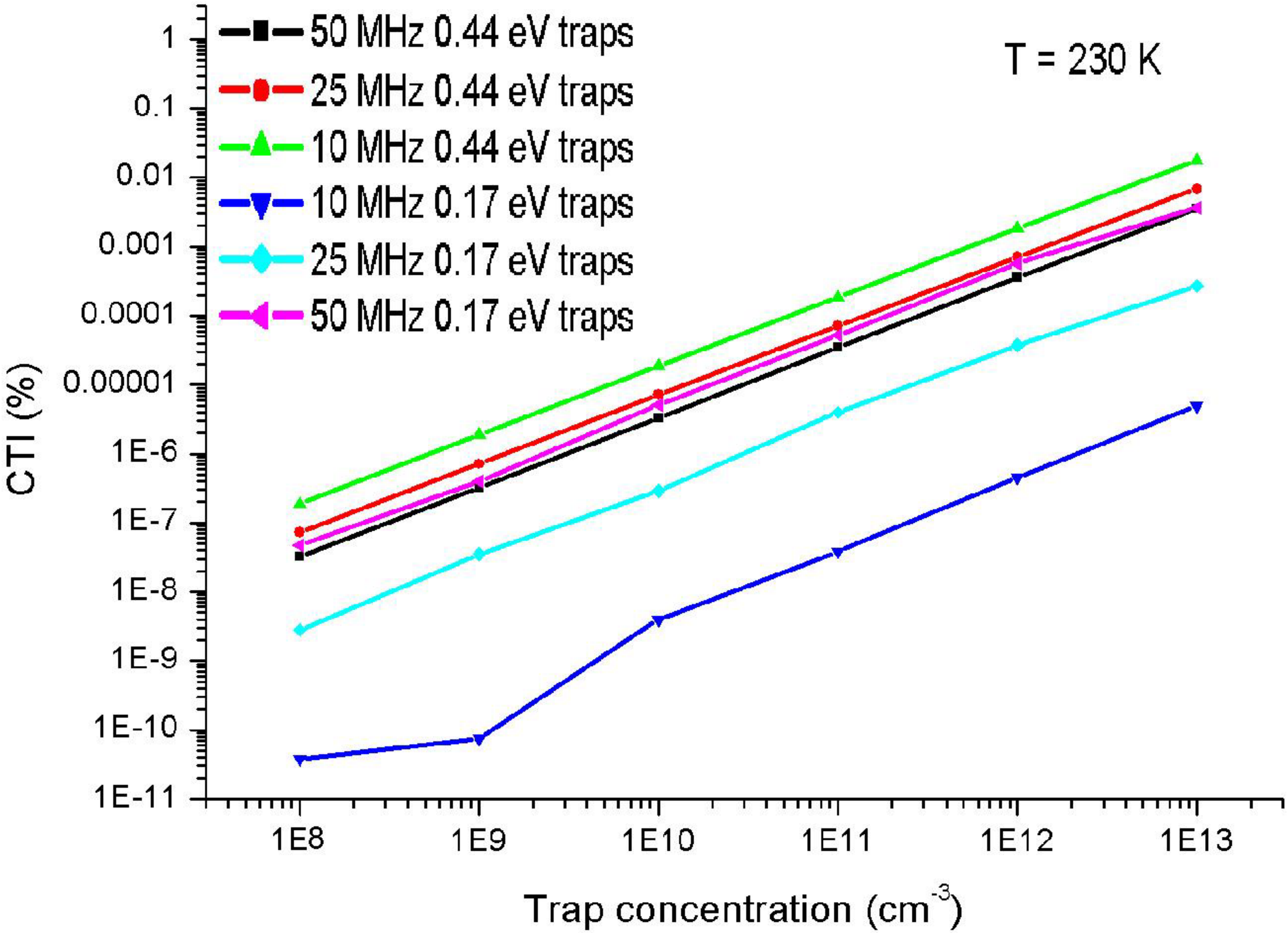
- trap energy levels (0.17 and 0.44 eV)
- clock frequency (10 to 50 MHz)
- temperature (130 to 440 K)
- trap concentration (10^8 to 10^{13}/cm^3)
- hit (pixel) occupancy (0.1% to 1%)
- trap energy level variation 0.17±0.005 eV

Clock-voltage induced CTI related to power consumption.

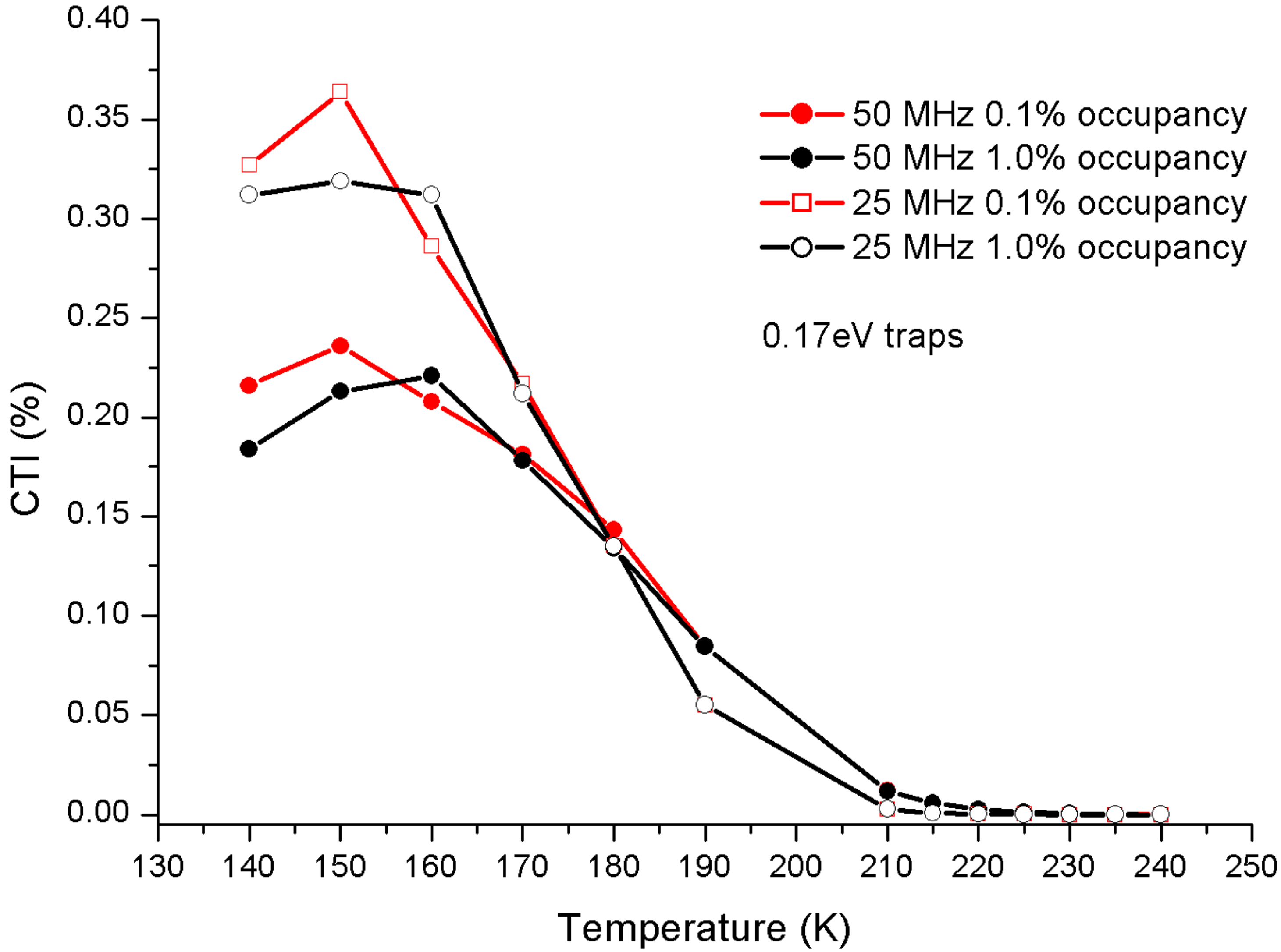
CTI: Temperatures and Different Frequencies



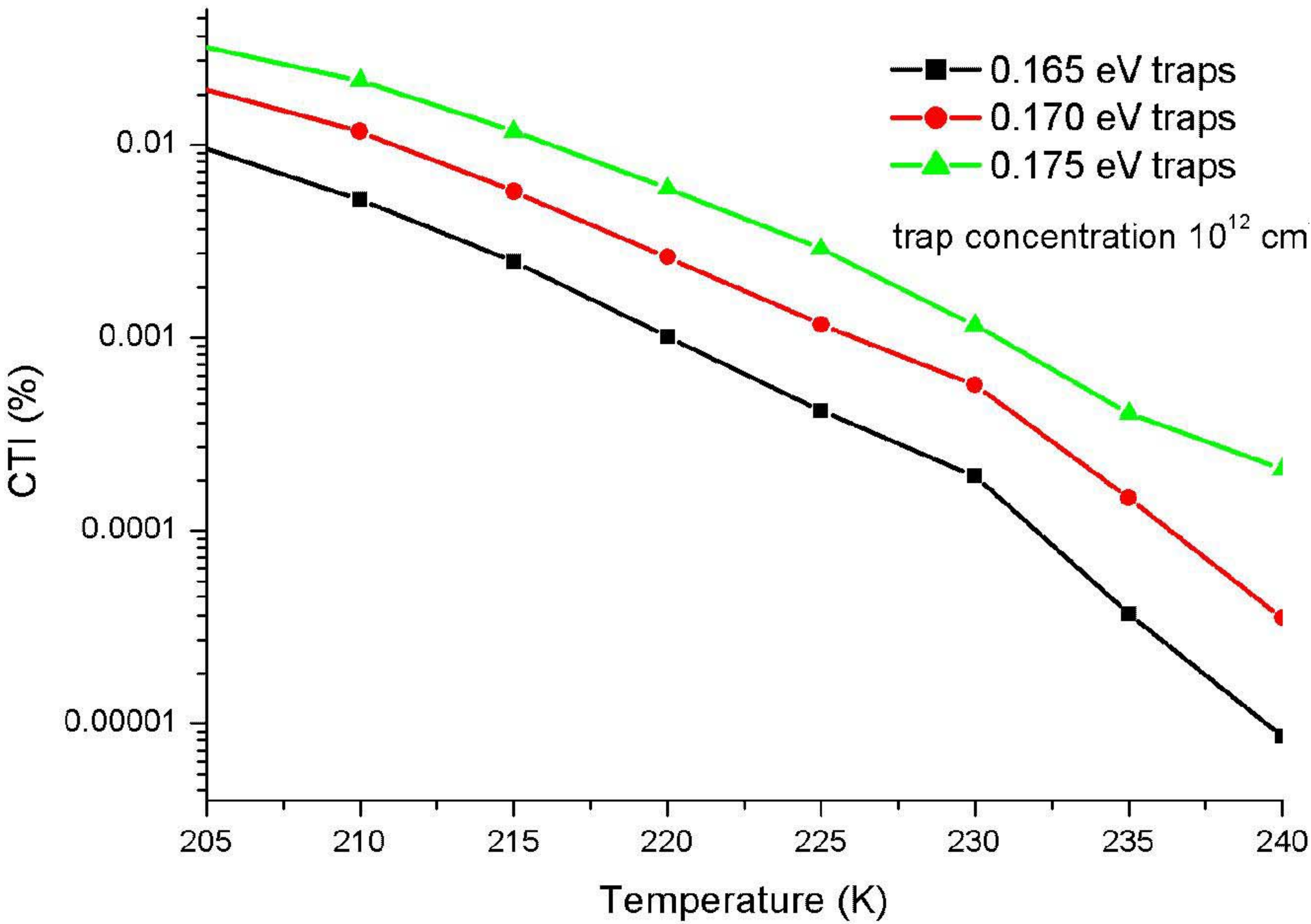
CTI: Trap Concentrations



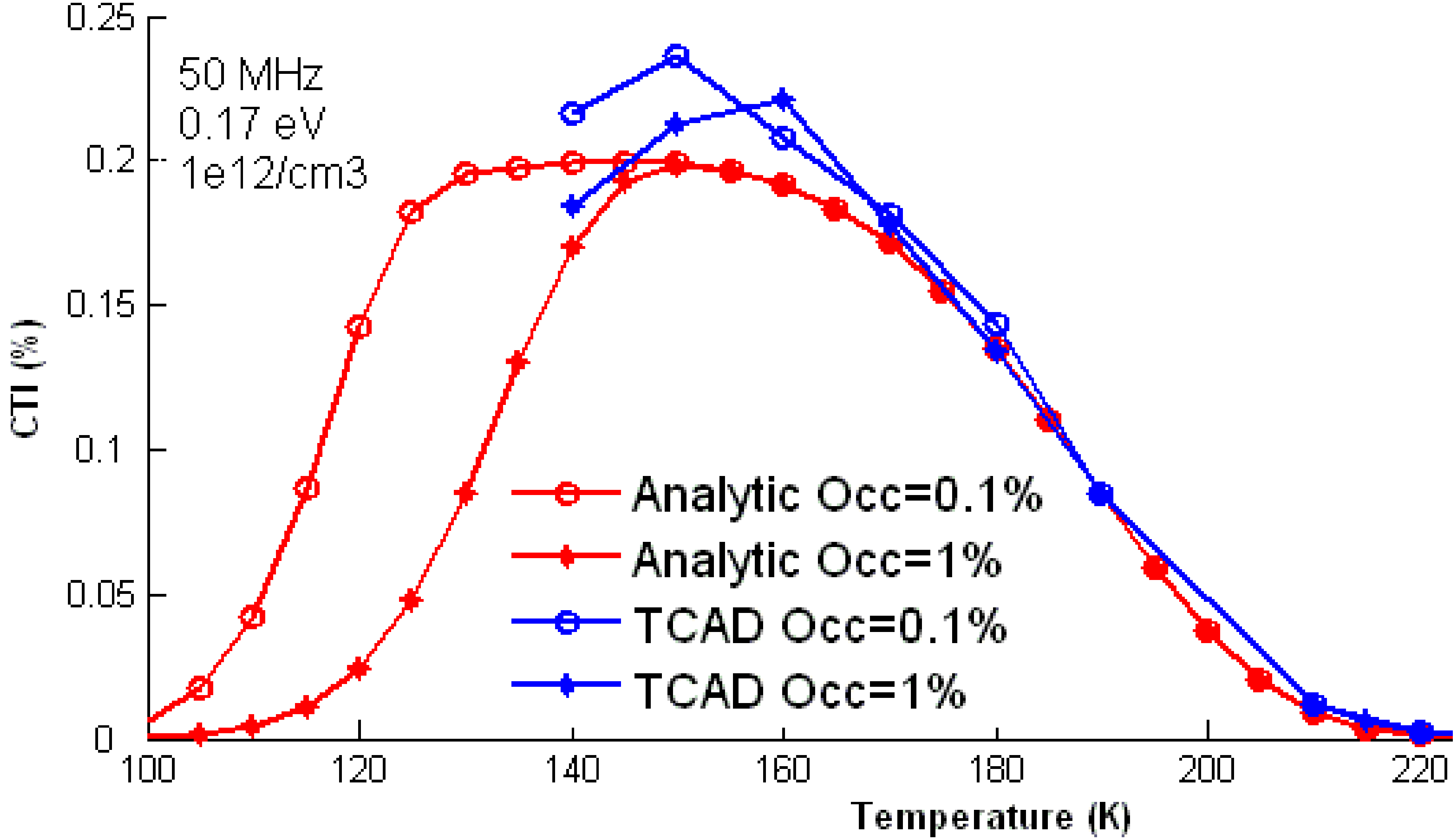
CTI: Hit (Pixel) Occupancies and Frequencies



CTI: Trap Energy Level Variations

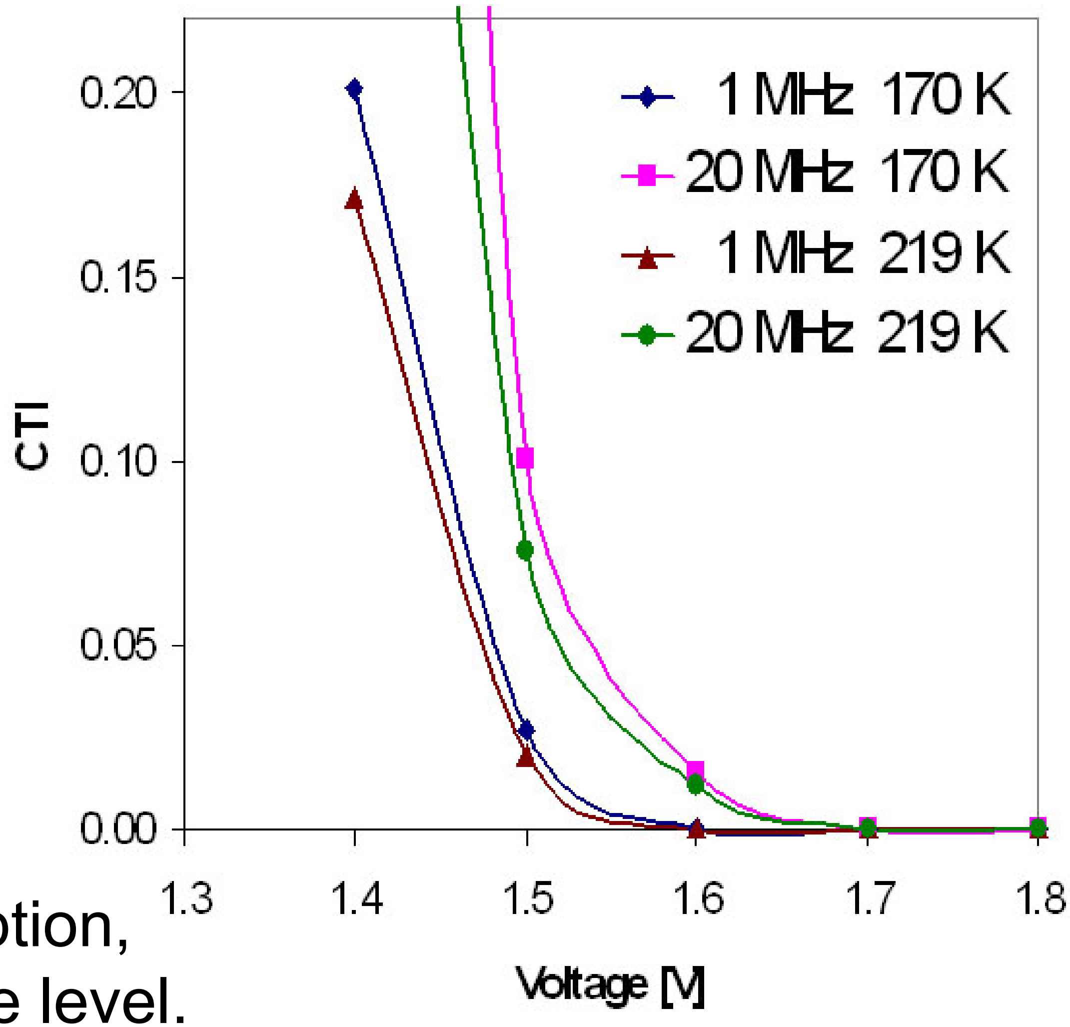


Analytic Model and Hit (Pixel) Occupancies



CTI as a Function of Voltage Applied to Gates (Clock Voltage Induced CTI)

• Un-irradiated device: small CTI ($< 10^{-6}$).
• decrease of clock voltage reduces transfer efficiency.



Find optimum clock voltage in order to
a) reduce power consumption,
b) keep CTI on acceptable level.

Experimental Setup at Liverpool University

Conclusions

- CCD with high-speed column-parallel readout simulated using the ISE-TCAD package with two trap energy levels.

- Optimal operation temperature about 230K to minimize CTI.

- CTI values determined for different

a) readout frequencies,
b) trap concentrations,
c) hit (pixel) occupancies,
d) variation of trap energy levels.

- Good agreement with expectations from analytical model.

- Comparison with data from irradiated CCDs essential.

- Test system in preparation to measure CTI for irradiated CCDs.

- High-speed CCD vertex detector development on track as vital part of a future ILC detector.