Radiation Resistance of a Two-Phase CCD Sensor

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MOTIVATION

CCDs will be used as tracking devices in the vertex detector of the future Linear Collider.

Near the interaction point there will be a radiation background from $e^{\pm}$ pairs and fast neutrons. It is expected the sensors to receive approximately 5×10^{12} electrons/cm^2 and $> 5\times10^{9}$ neutrons/cm^2 during their 10-year service.

To ensure long-term and reliable work of the CCD sensors, study of the radiation damage effects becomes one of the important R&D issues.

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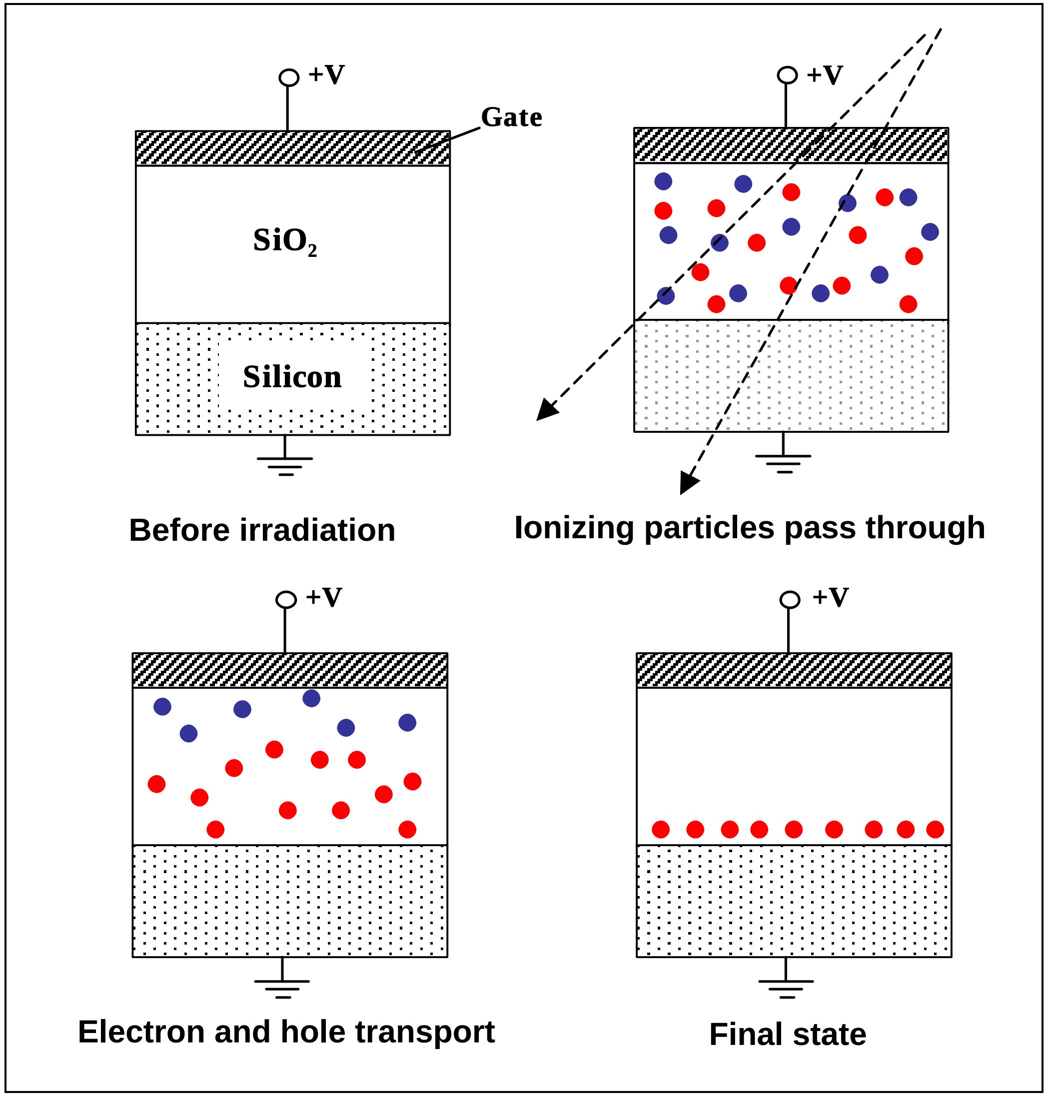
RADIATION DAMAGE – SURFACE EFFECTS



- Permanent ionization effects in the insulating oxides

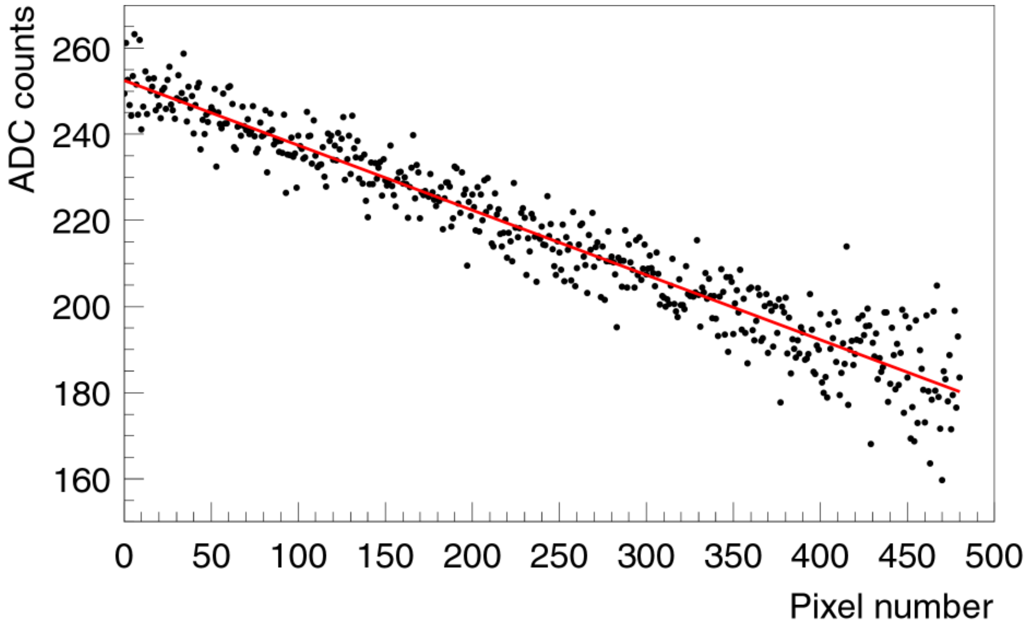
→ Shift of the amplitude of the drive pulses and of the DC bias needed for proper operation of the CCD,

- Increase of the interface state defect density

→ More dark current generated at the Si-SiO_2 interface,

RADIATION DAMAGE – BULK EFFECTS

- **Displacement damage (bulk damage) ➡ Dark current, loss of signal charge during transfer and increased readout noise.**



Capture of signal electrons by bulk defects causes Charge Transfer Inefficiency (CTI).

THE CHALLENGE

To suppress the influence of the radiation damage, CCD's usually have to operate at low temperature (e.g. –120°C). That causes several problems due to:

- **Thermal distortions of the chips and their supporting frames caused by the cooling to low temperature;**
- **Complicated support frame;**
- **Increased amount of material between the collision point and outer detectors.**

Significant improvement of the vertex detector performance can be achieved if CCD's can operate at near-room temperature.

DIFFICULTIES

- **High dark current in irradiated CCD. However, by using Multi-Pinned Phase mode (MPP) the dark current generation from the Si-SiO_2 interface (dominant in buried channel CCDs) can be reduced at least one order of magnitude.**
- **It is not possible to make CTI to be virtually zero, as for low-temperature operation ➡ We have to live with some CTI.**

The signal at the output should be high enough to ensure good S/N ratio.

CTI PROBLEM

To increase the output signal and S/N ratio of the CCD:

**To increase the generated signal itself,
i.e. to use thicker epitaxial layer (> 30μm ?)**

Vertex detector should be physically thin

**To reduce the charge transfer losses,
i.e. to have lower Charge Transfer Inefficiency (CTI)**

1. Select proper operating conditions

2.Use background charge (fat zero)

3. “Low CTI” CCD design

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LOWER CTI

- **Proper operating conditions:**
  - · **1. Timing (readout frequency, widths of shift pulses),**
  - **2. Temperature – limited around 0 ¸ +10 °C.**
- **Background charge (fat zero):**
  - · **1. In the horizontal register**
  - ? **2. In the vertical register**
- **“Low CTI” CCD design:**
  - · **1. “Notch” CCD**
  - · **2. Smaller pixels**

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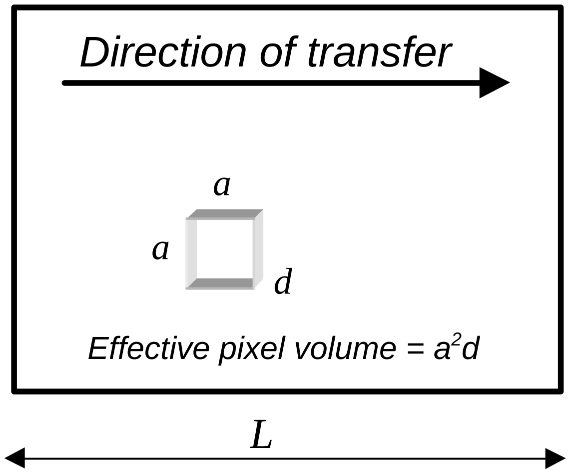
SMALLER PIXELS - LOWER CTI

If the volume occupied by the signal charge is considered constant, then:

$$\mathrm{CTI} = \frac{n_t}{n_s} F(\text{temperature, timing, type of defects}),$$

where n_t **is the defect concentration, and** n_s **is the concentration of signal electrons.**

Number of electrons left of signal packet of N_0 **electrons after** m **transfers is:**



$$N_m = N_0(1 - CTI)^m \approx N_0(1 - mCTI)$$

Number of transfers $m = \frac{L}{a}$**, therefore**

$$N_m \approx N_0(1 - \frac{L}{a} CTI) = N_0(1 - \frac{L}{a}\frac{n_t}{n_s} F)$$

$$N_m \approx N_0(1 - \frac{L}{a}\frac{n_t}{N_0} F a^2 d) = N_0(1 - L\frac{n_t}{N_0} F a d)$$

For CCDs with the same register length, smaller charge losses has the one with smaller pixel size.

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CCD PARAMETERS

Measurable parameters of the CCD and their change under irradiation:

1. Increased dark current
2. Shift of the drive pulse voltages needed for normal operation
3. Increased charge-transfer inefficiency (CTI)
4. Dark current spikes (“hot pixels”)

Experimental conditions:

- Irradiation with a ^{90}Sr source or a ^{252}Cf source at room temperature,
- CCD grounded or under normal operating conditions (clocked and biased),
- Readout cycle 3 seconds, time to read the CCD at 250kpix/s is 1.3s,
- CTI measurement using charge packets of 1620e^{-}.

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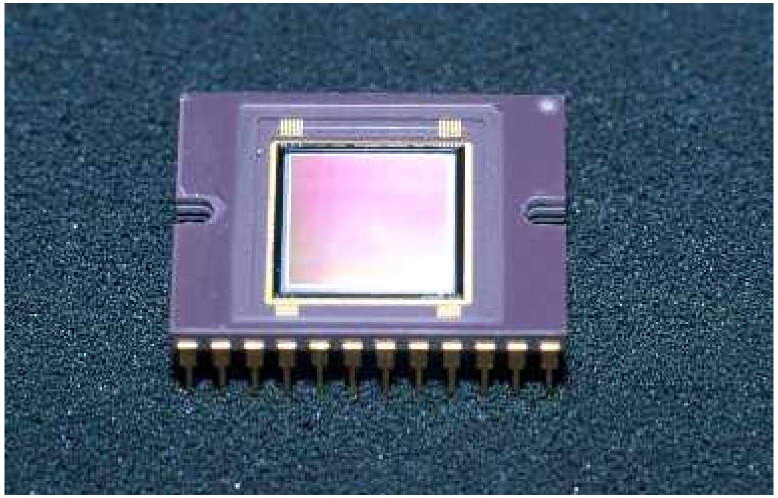
CCD UNDER STUDY

Hamamatsu S5466:

- **Buried channel,**
- **Two-phase transfer,**
- **512×512 imaging pixels,**
- **24μm×24μm pixel size,**
- **10μm epitaxial layer,**
- **Full-Frame Transfer,**
- **Multi-Pinned Phase mode (MPP).**



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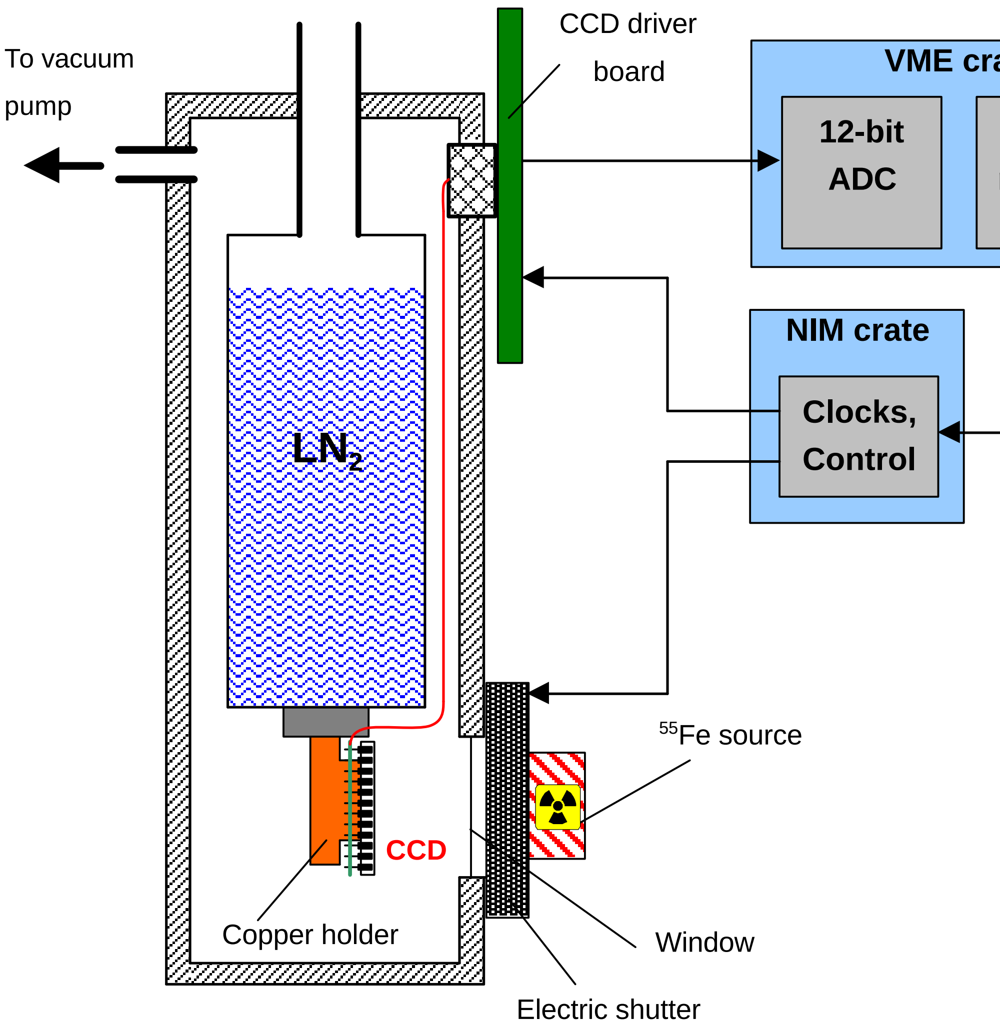
EXPERIMENTAL SETUP



Vacuum cryostat VPF-100

Variable temperature 79-350K
Stability ±0.1K

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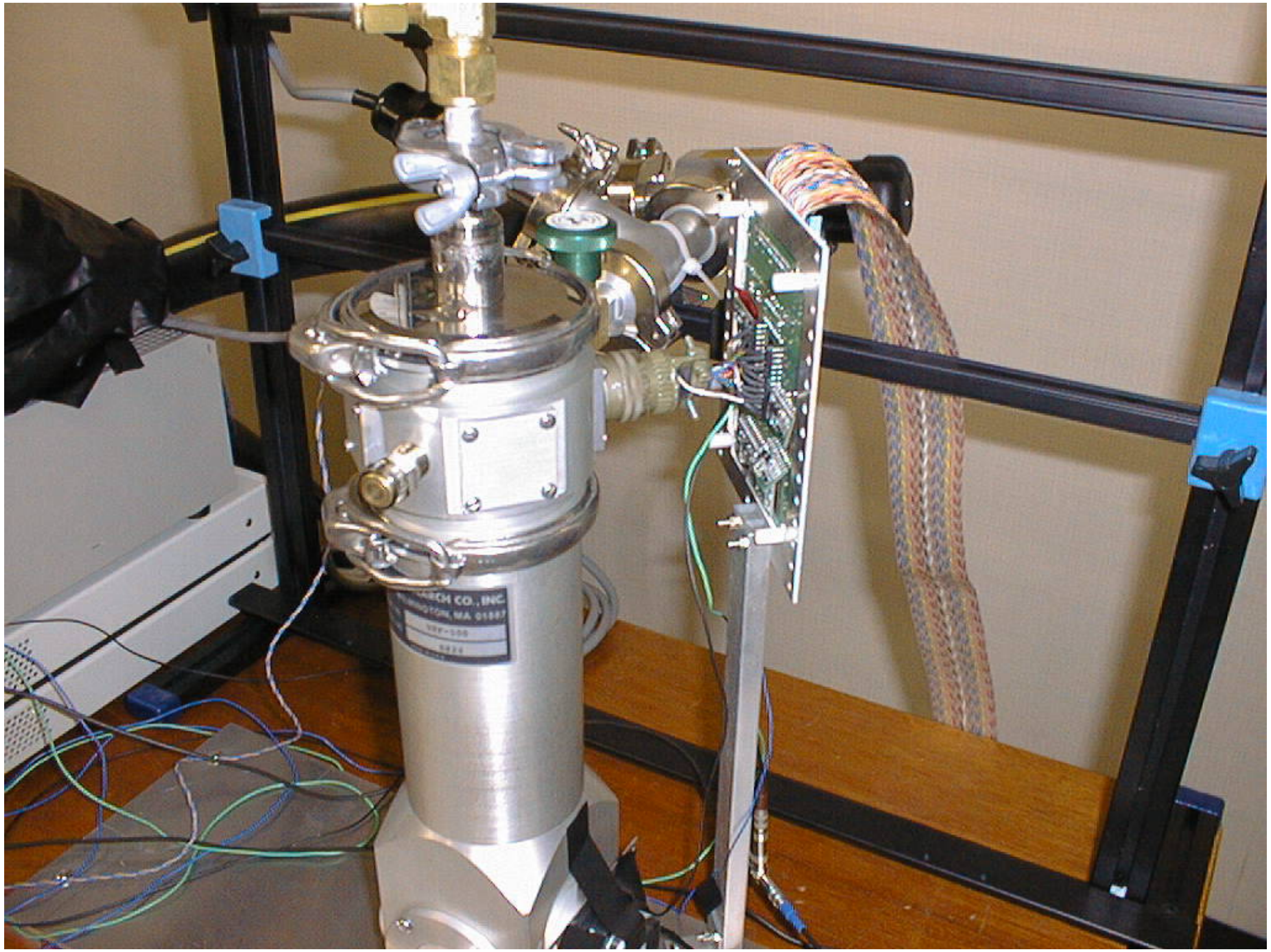
EXPERIMENTAL SETUP



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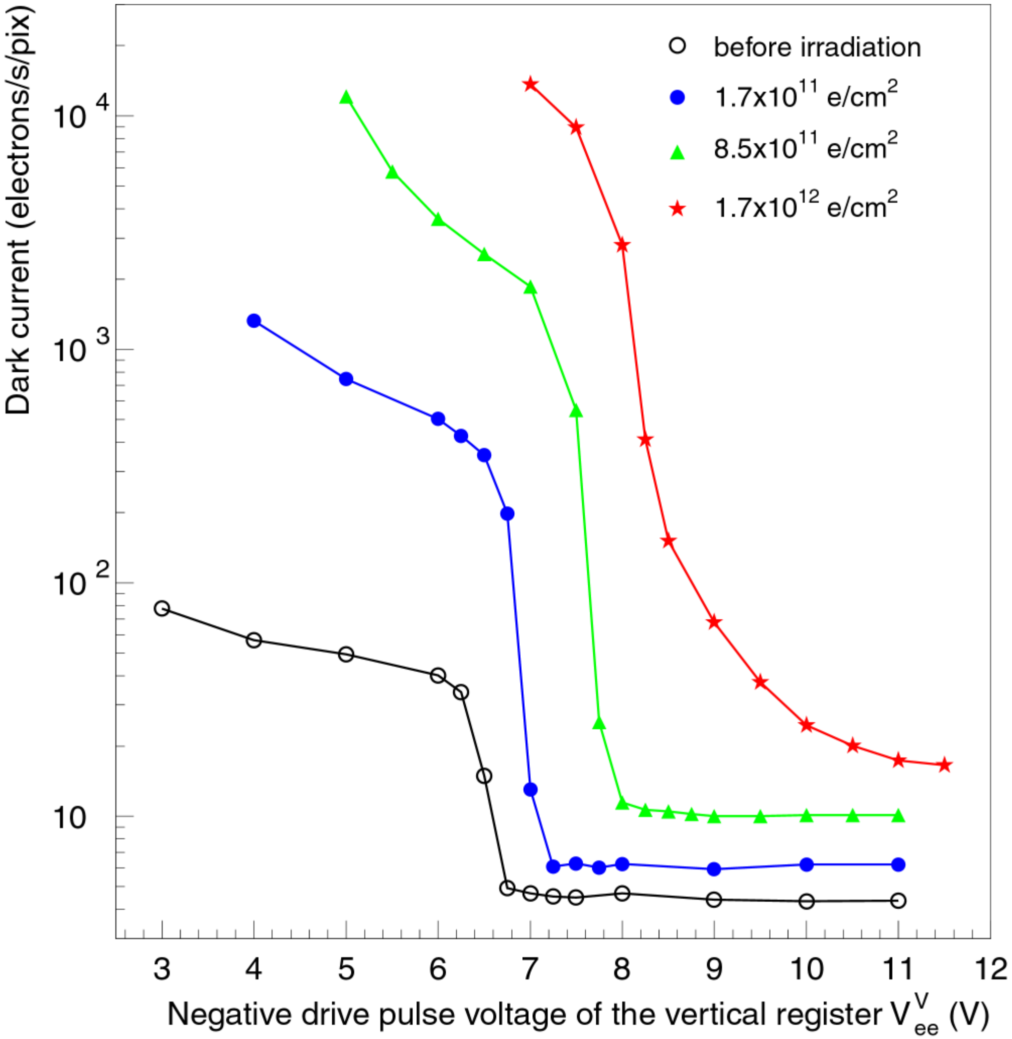
EXPERIMENTAL RESULTS – DARK CURRENT



Electron Irradiation

Dark current versus the voltage applied to the imaging section during accumulation, at -26°C.

- **Change of the MPP threshold voltage V_{ee}^{MPP}**
- **Increase of the dark current caused by bulk and interface defects**

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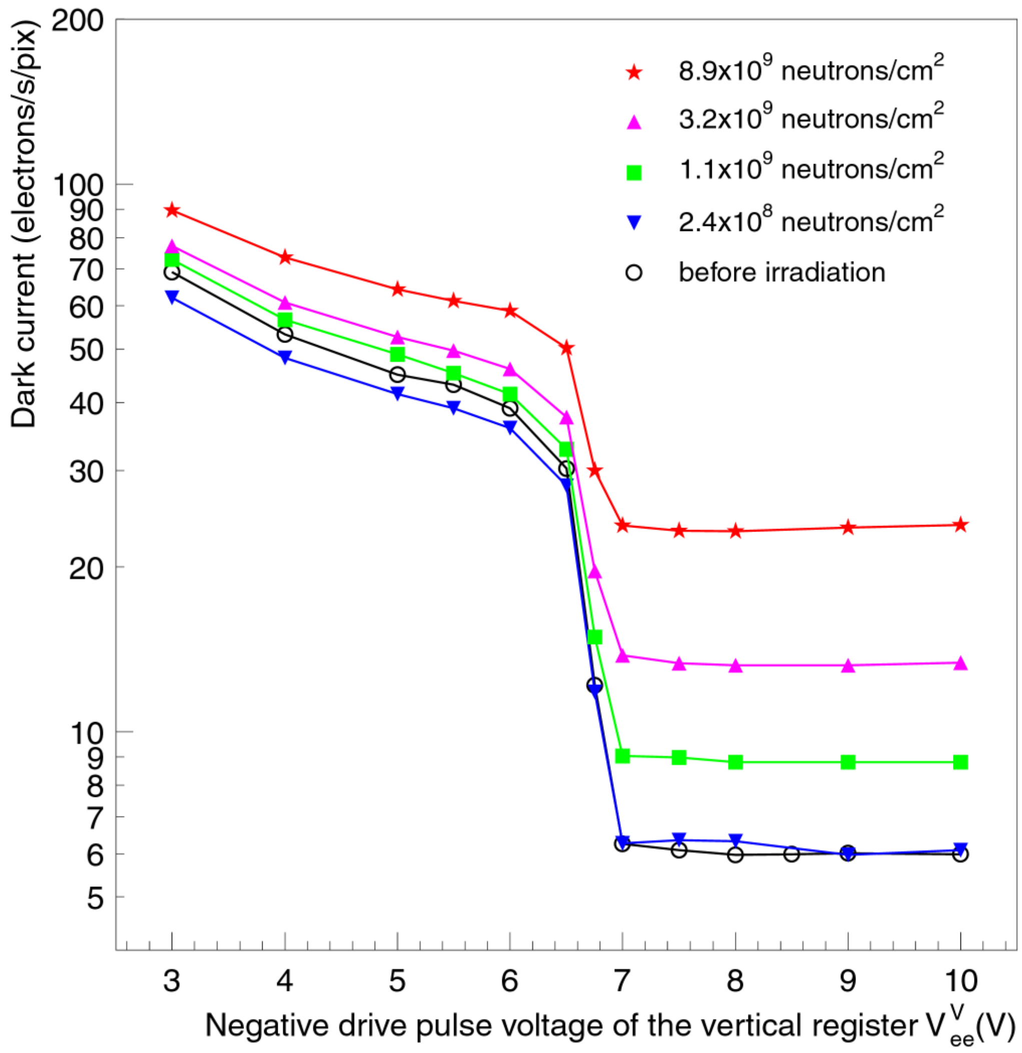
EXPERIMENTAL RESULTS – DARK CURRENT



Neutron Irradiation

Dark current versus the voltage applied to the imaging section during accumulation, at -26°C.

- **Increase of dark current due solely to bulk defects**
- **The MPP threshold voltage V_{ee}^{MPP} does not change**

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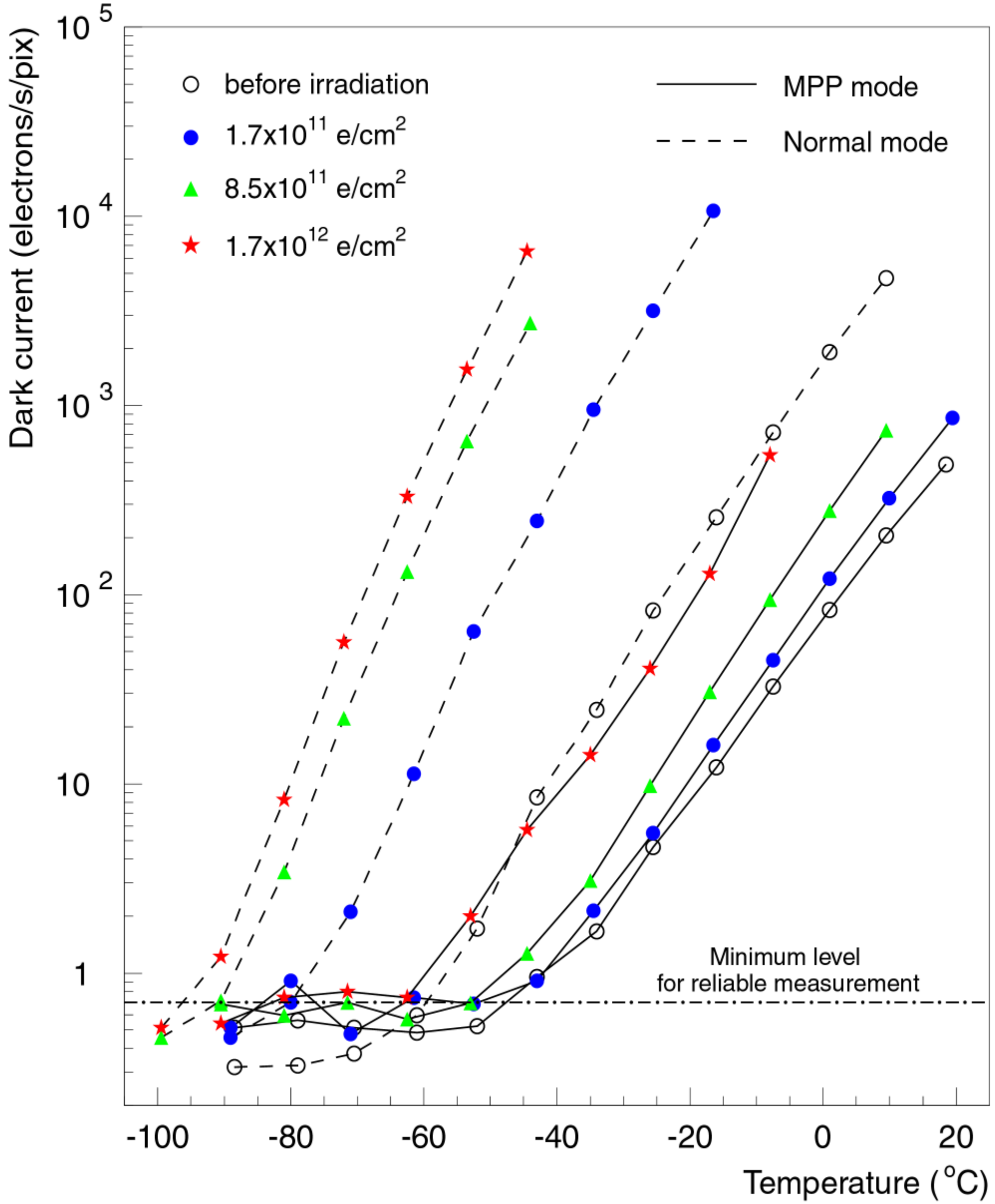
EXPERIMENTAL RESULTS – DARK CURRENT



Electron Irradiation

Dark current versus temperature for normal and MPP mode of operation.

- **The power of MPP mode to reduce the dark current**

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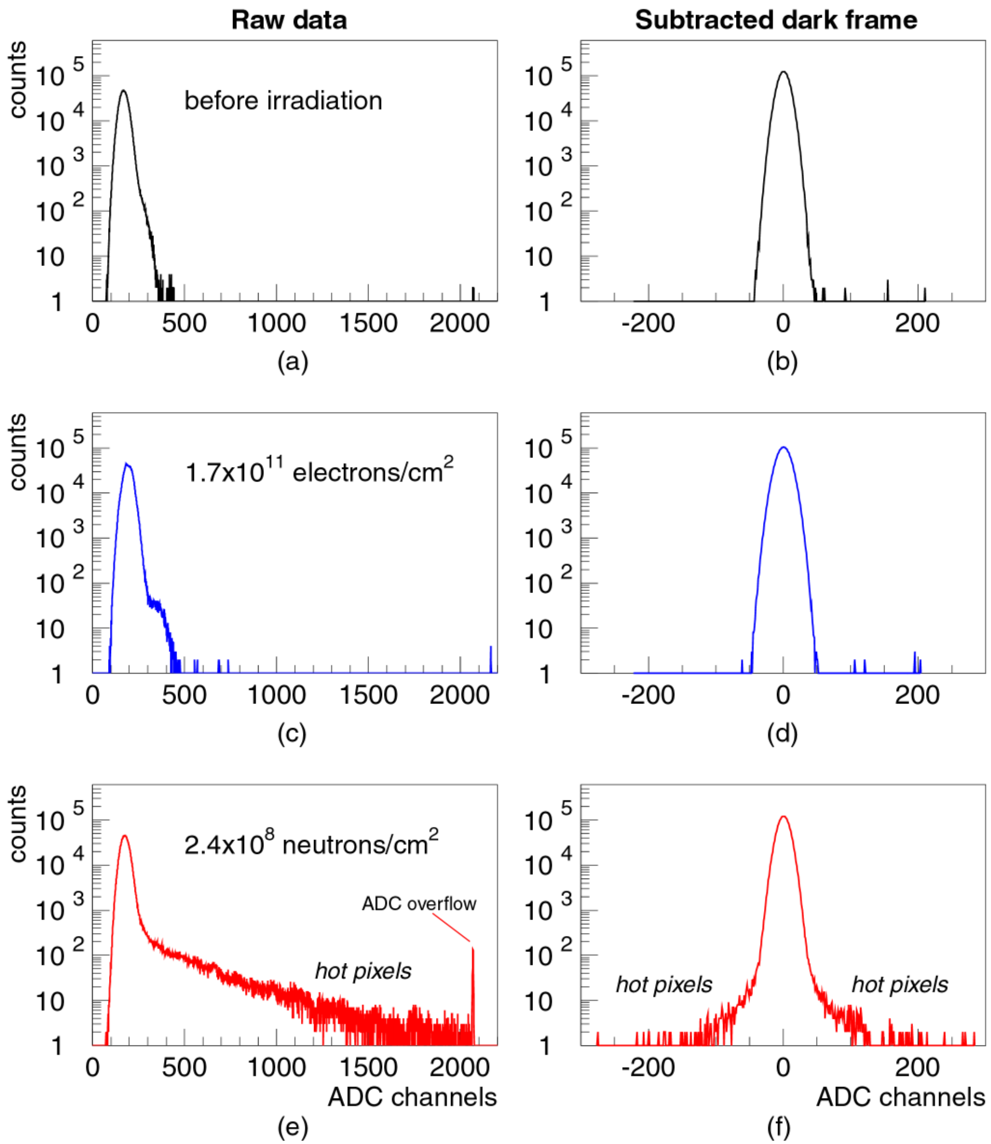
EXPERIMENTAL RESULTS – HOT PIXELS



Neutron Irradiation

Dark current distribution at +10°C.

After subtraction of the average dark current individually for each pixel, dark current spikes are significantly suppressed.

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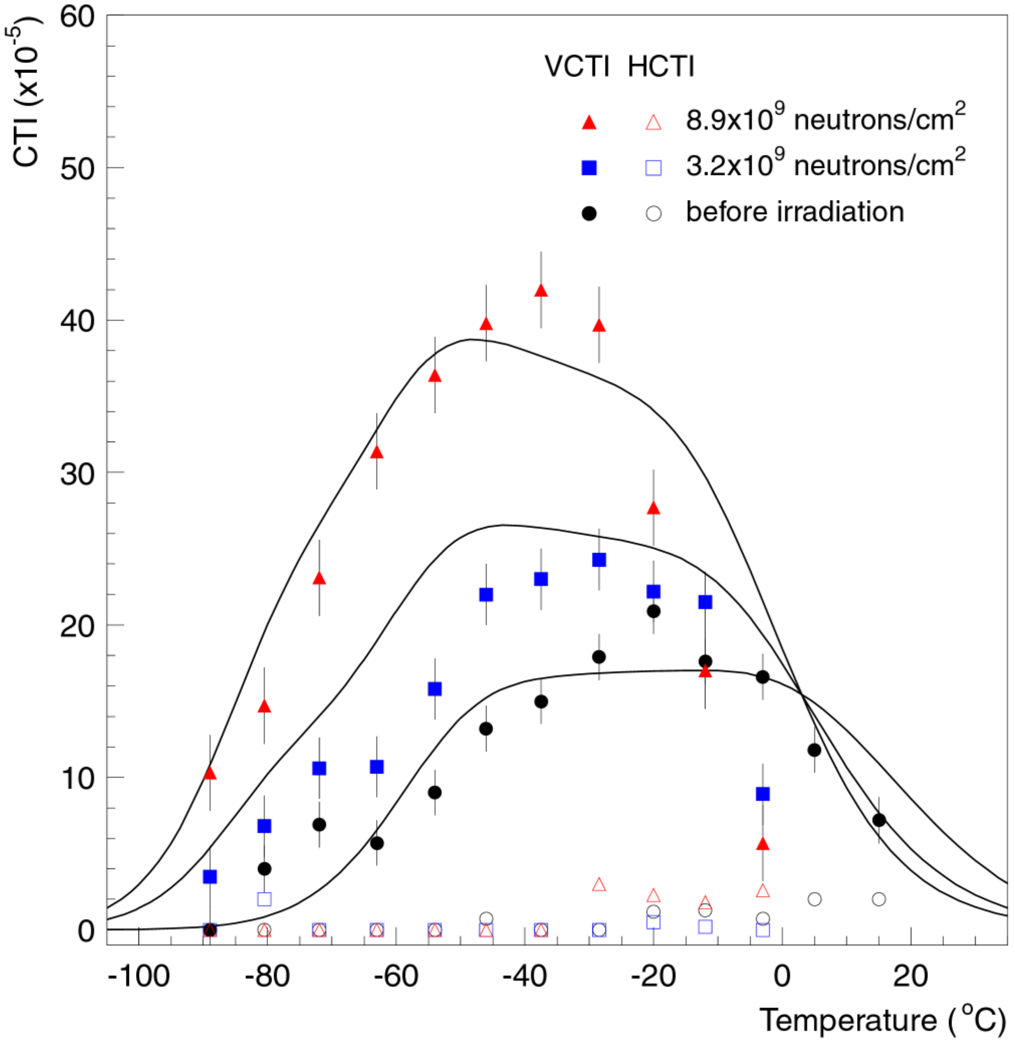
EXPERIMENTAL RESULTS – CTI



Neutron Irradiation

Charge Transfer Inefficiency of the vertical (parallel) register (VCTI) and of the horizontal (serial) register (HCTI)

A CTI model has been developed and applied to the CCDs

Two defects are introduced:

- **E_c - 0.39 eV - divacancy (*V-V*$^{-}$)**
- **E_c - 0.44 eV - *P-V* complex**

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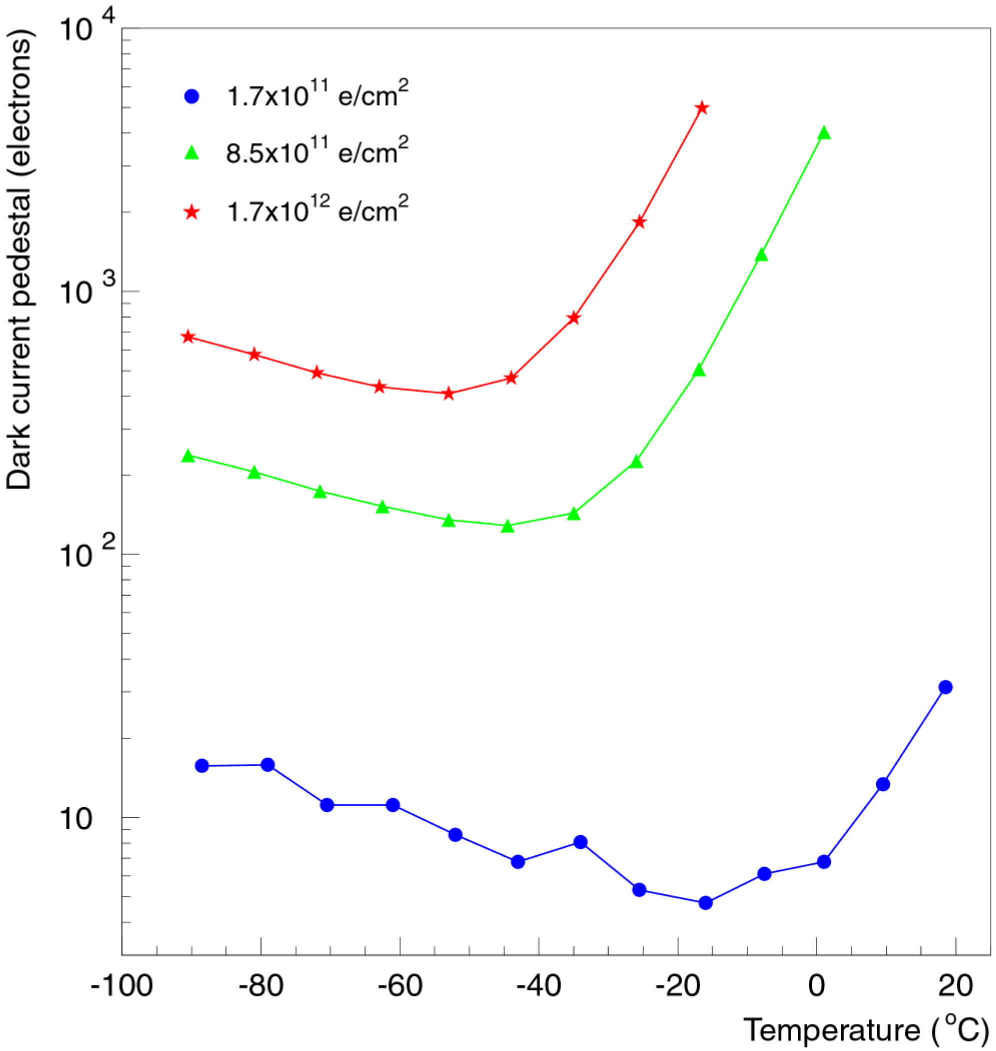
EXPERIMENTAL RESULTS – SPURIOUS DARK CURRENT



Electron Irradiation

Spurious dark current was observed

- **only in electron irradiated devices**
- **only in MPP mode**
- **produced by the clocking**

- **provides intrinsic “fat zero” effect**
- **caused by impact ionization by holes**

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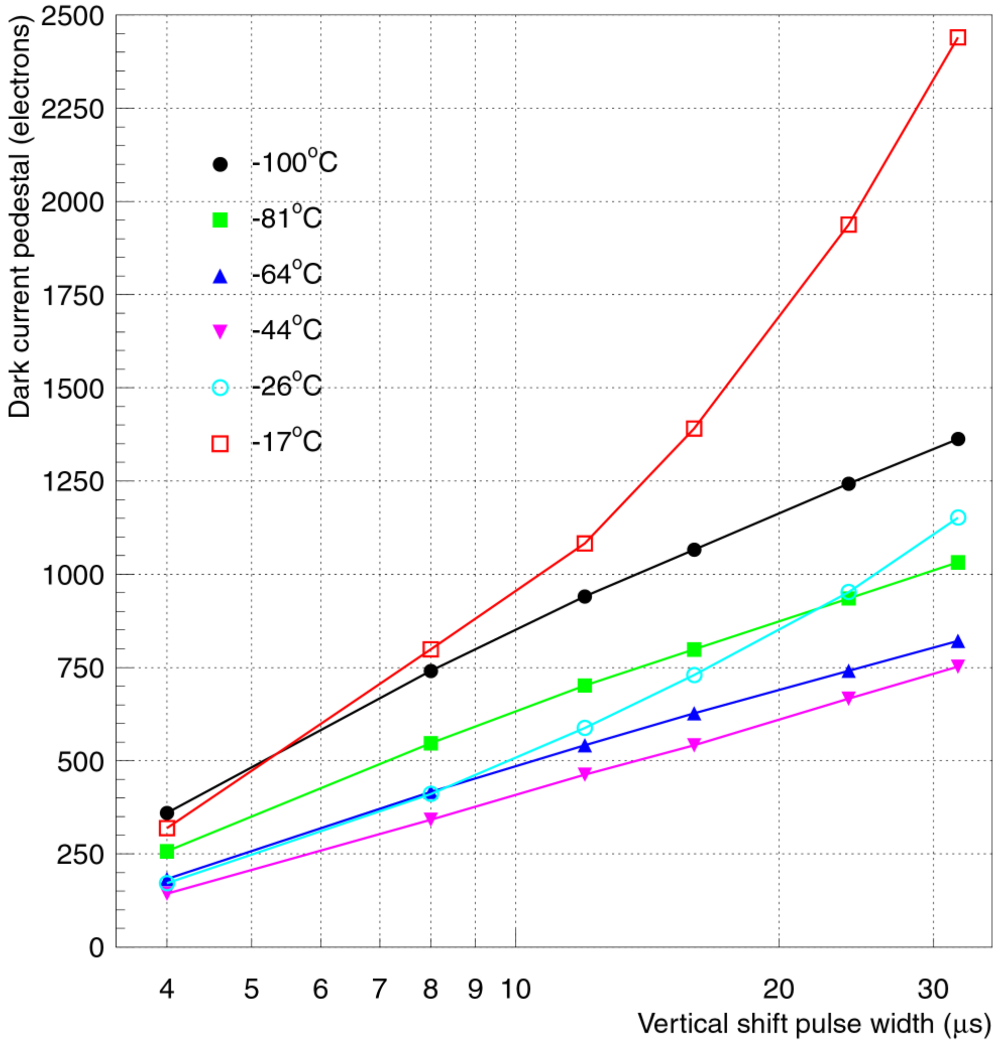
EXPERIMENTAL RESULTS– SPURIOUS DARK CURRENT



Electron Irradiation

- **DCP is generated in the imaging part of the CCD**
- **depends on the amplitude of the vertical shift pulse**
- **depends on the width of vertical shift pulse**

→ Can be controlled

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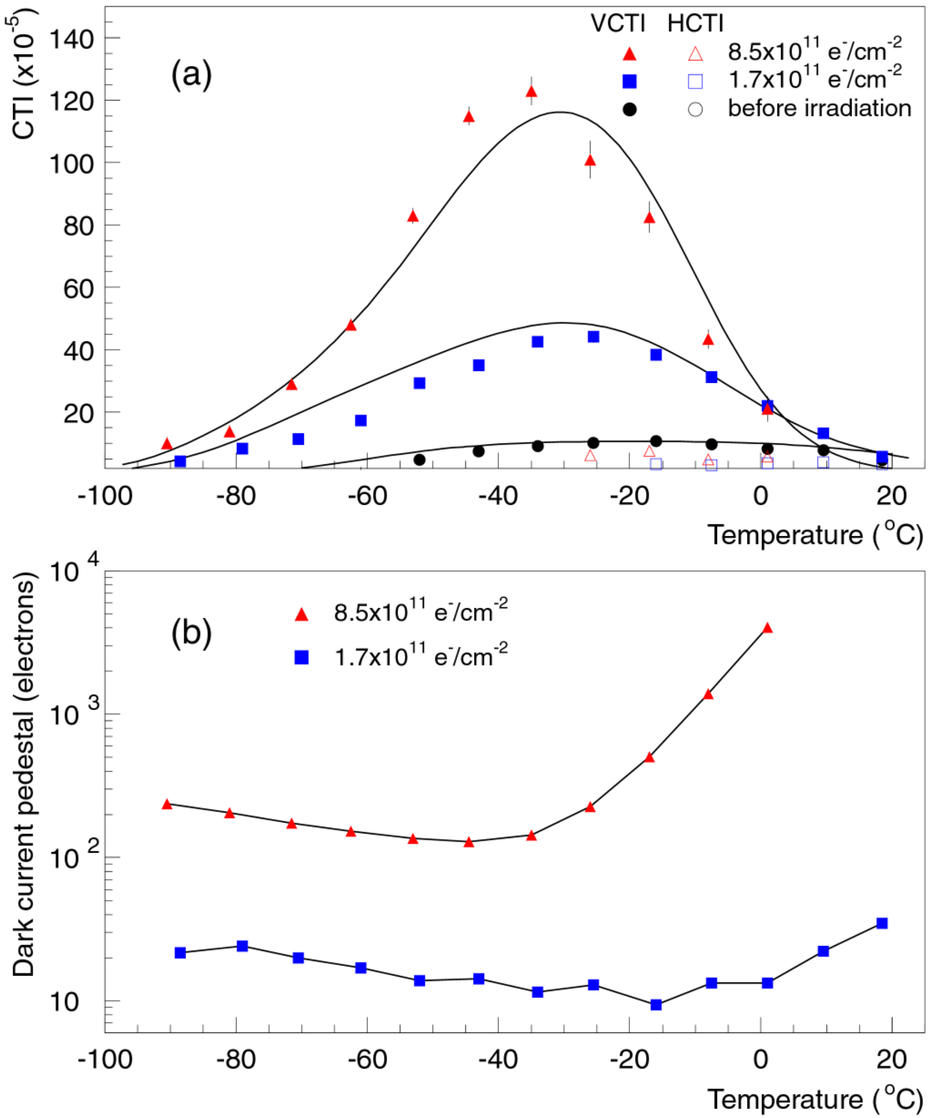
EXPERIMENTAL RESULTS - CTI



Electron Irradiation

- **The same defects at E_c - 0.39 eV and E_c - 0.44 eV cause CTI**
- **CTI decreased by the "fat zero" effect**
- **Vertical CTI is dominant**

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SUMMARY

- **Radiation resistance of a two-phase CCD to b-rays and fast neutrons has been studied,**
- **Increased dark current and CTI are observed, as well as significant surface damage effects,**
- **A model for the CTI in two-phase CCD is developed and applied,**
- **Dark current spikes, caused by neutron irradiation are observed. We think the neutron background will not be a problem,**
- **Additional spurious dark current is observed after electron irradiation. It is caused by surface damage defects.**

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FUTURE PLANS

- **After completing the study, we will know the maximum possible CTI reduction at near-room temperature using only proper operating conditions and injection of fat zero charge.**
- **Similar experiments are being carried out on faster CCDs (10Mpix/s).**
- **Future investigations will use CCDs featuring SiO_2 – Si_3N_4 dielectric system.**

This presentation is based on the following papers:

1. K.D. Stefanov et al, “Investigation of the Radiation Performance of CCD Sensors in a Vertex Detector Application”, Nucl. Instr. Methods, vol. A436, pp. 182-187 (1999).
2. K.D. Stefanov et al, “Electron and Neutron Radiation Damage Effects on a Two-Phase CCD”, KEK Preprint 99-114 (1999), submitted to IEEE Transactions on Nuclear Science.