Radiation Resistance of a Two-Phase CCD Sensor

K. D. Stefanov, T. Tsukamoto, Saga University
A. Miyamoto, Y. Sugimoto, KEK
N. Tamura, Niigata University
K. Abe, T. Nagamine, Tohoku University
T. Aso, Toyama National College of Maritime Technology

7th International Conference on Instrumentation for Colliding Beam Physics,
Hamamatsu, 15-19 November, 1999
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 $5 \times 10^{12}$ electrons/cm$^2$ and $> 5 \times 10^9$ 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.
Radiation Resistance of a Two-Phase CCD Sensor

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-SiO₂ interface,
Radiation Resistance of a Two-Phase CCD Sensor

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).
Radiation Resistance of a Two-Phase CCD Sensor

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.
Radiation Resistance of a Two-Phase CCD Sensor

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.
Radiation Resistance of a Two-Phase CCD Sensor

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

Vertex detector should be physically thin

1. Select proper operating conditions
2. Use background charge (fat zero)
3. “Low CTI” CCD design
Radiation Resistance of a Two-Phase CCD Sensor

LOWER CTI

● Proper operating conditions:
  1. Timing (readout frequency, widths of shift pulses),
  2. Temperature – limited around 0 $\div$ +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
Radiation Resistance of a Two-Phase CCD Sensor

**SMALLER PIXELS - LOWER CTI**

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

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

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:

\[ N_m = N_0 (1 - \text{CTI})^m \approx N_0 (1 - m\text{CTI}) \]

Number of transfers \( m = \frac{L}{a} \), therefore

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

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

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

**Direction of transfer**

**Effective pixel volume** = \( a^2 d \)
Radiation Resistance of a Two-Phase CCD Sensor

CCD PARAMETERS

Measureable 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 $^{90}\text{Sr}$ source or a $^{252}\text{Cf}$ 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$^-$.
Radiation Resistance of a Two-Phase CCD Sensor

CCD UNDER STUDY

Hamamatsu S5466:

- Buried channel,
- Two-phase transfer,
- $512 \times 512$ imaging pixels,
- $24 \mu m \times 24 \mu m$ pixel size,
- $10 \mu m$ epitaxial layer,
- Full-Frame Transfer,
- Multi-Pinned Phase mode (MPP).
Radiation Resistance of a Two-Phase CCD Sensor

**EXPERIMENTAL SETUP**

- Copper holder
- Electric shutter
- LN$_2$
- To vacuum pump
- Vacuum cryostat VPF-100
  - Variable temperature 79-350K
  - Stability ±0.1K
- CCD
- $^{55}$Fe source
- Window
- CCD driver board
- NIM crate
  - Clocks, Control
- VME crate
  - 12-bit ADC
  - I/O register
- HP-UX UNIDAQ V2.3
Radiation Resistance of a Two-Phase CCD Sensor

EXPERIMENTAL SETUP
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
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 $V_{ee}^{\text{MPP}}$ does not change
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
Radiation Resistance of a Two-Phase CCD Sensor

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.
Radiation Resistance of a Two-Phase CCD Sensor

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:

- $E_c - 0.39 \text{ eV}$ - divacancy (V-V)
- $E_c - 0.44 \text{ eV}$ - $P-V$ complex
Radiation Resistance of a Two-Phase CCD Sensor

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
Radiation Resistance of a Two-Phase CCD Sensor

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
Radiation Resistance of a Two-Phase CCD Sensor

**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.
Radiation Resistance of a Two-Phase CCD Sensor

**SUMMARY**

- Radiation resistance of a two-phase CCD to $\beta$-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.
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$_3$N$_4$ dielectric system.

This presentation is based on the following papers:
