Observation of Gamma Irradiation-Induced Suppression of Reverse Annealing in Neutron Irradiated MCZ Si Detectors

Zheng Li[1], Rubi Gul[1], Jaakko Harkonen[2], Martin Hoeferkamp[3], Jim Kierstead[1], Jessica Metcalfe[3], and Sally Seidel[3]

[1]Brookhaven National Laboratory, Upton, NY 11973, USA
[2]Helsinki Institute of Physics, Finland
[3]University of New Mexico, NM, USA

12th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders Ljubljana, Slovenia, 2-4 June 2008

**This research was supported by the U.S. Department of Energy: Contract No. DE-AC02 -98CH10886*

Outline

1. **Motivation of mixed radiations**

2. **Experimental Overview: samples, radiations and measurements**

3. **Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation**

4. **Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and RT reverse anneal:**
   a) no gamma radiation during the anneal (control)
   b) with gamma radiation during the anneal

5. **Discussion**

6. **Summary**

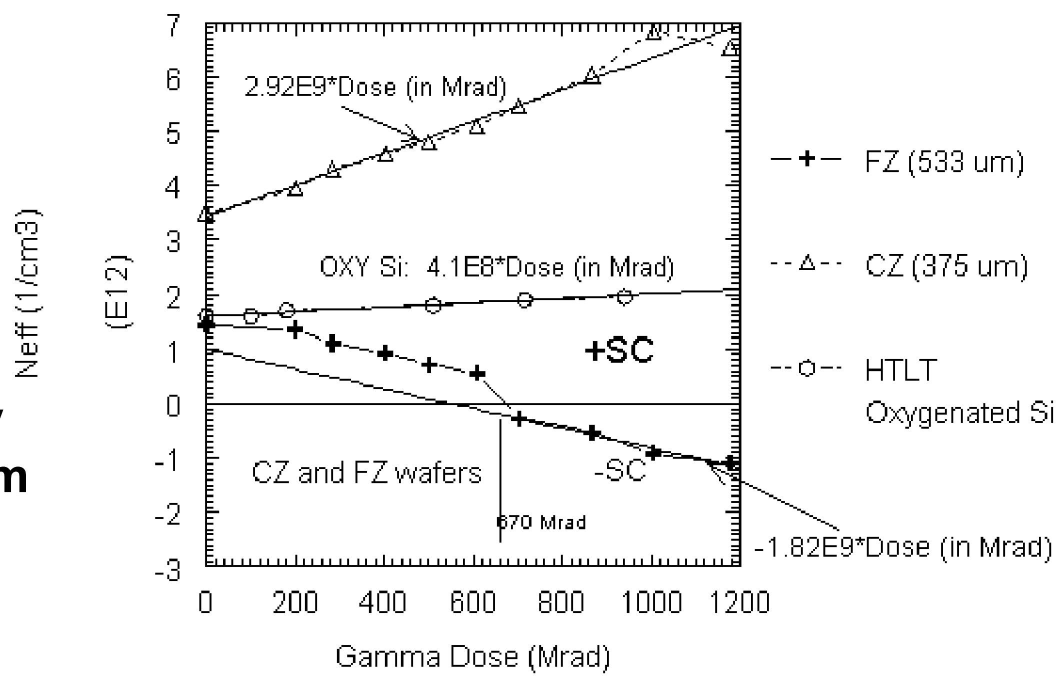
Motivation of mixed radiations

- For the development of radiation-hard Si detectors for the SiD BeamCal program for the ILC
  - In the ILC radiation environment, there will be gamma/e and neutron radiation

- Gamma irradiation is known to induce +SC in MCZ Si [1]

- The one year neutron fluence at the ILC is: Φ_{neq} = 2.68x10^{14} n_{eq}/cm^2. The one year gamma radiation dose is 10^9 rads =10^3 Mrads.

- -SC by n and +SC by gamma may just cancel each other --- minimum net SC and V_{fd}!



1. Z.Li,et al.,IEEE Trans.Nucl.Sci.NS-51 (4)(2004)1901.

Experimental: samples, radiations and measurements

- **Samples**:

n-type MCZ Si, 390 μm, 0.25cm^2, 1000 Ω-cm, as-processed p^+-n-n^+ structure (processed at BNL)

Sample #: / Conditions:	1480-5	1480-13	1480-15	1480-16
1st Radiation: Neutron (n_{eq}/cm^2)	$1.5x10^{14}$	$1.5x10^{14}$	$3x10^{14}$	$3x10^{14}$
2nd Radiation: Gamma (Mrad)	500	0	0	500

All samples were RT annealed after n-irradiation during the 5.5 month gamma radiation period

Radiations:

Neutrons: 0.8-1 MeV (HF=1.3), 1.5-3x10^{14} n_{eq}/cm^2, Annular Core Research Reactor in Sandia National Lab

Gamma: 1.25 MeV ^{60}Co, BNL, up to 500 Mrads

- **Experimental technique**: IV, CV, and TCT [2] with red (660 nm) laser (measured at BNL)

2. V. Eremin, N. Strokan, E. Verbitskaya and Z. Li, NIM A 372 (1996) 388-298

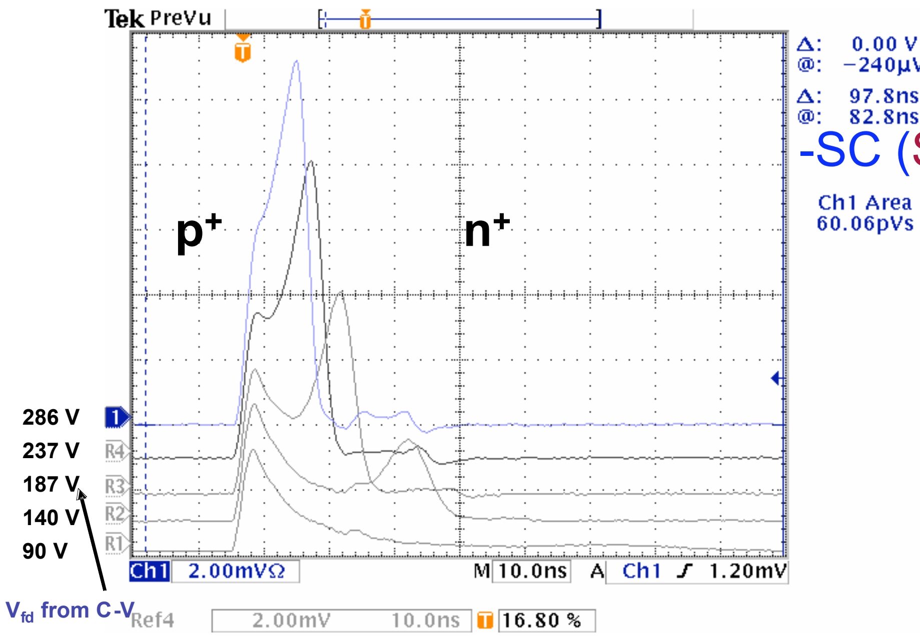
Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and beneficial anneal

$1.5 \times 10^{14}\ n_{eq}/cm^2$

1480-13, $1.5 \times 10^{14}\ n/cm^2$ (22 d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+

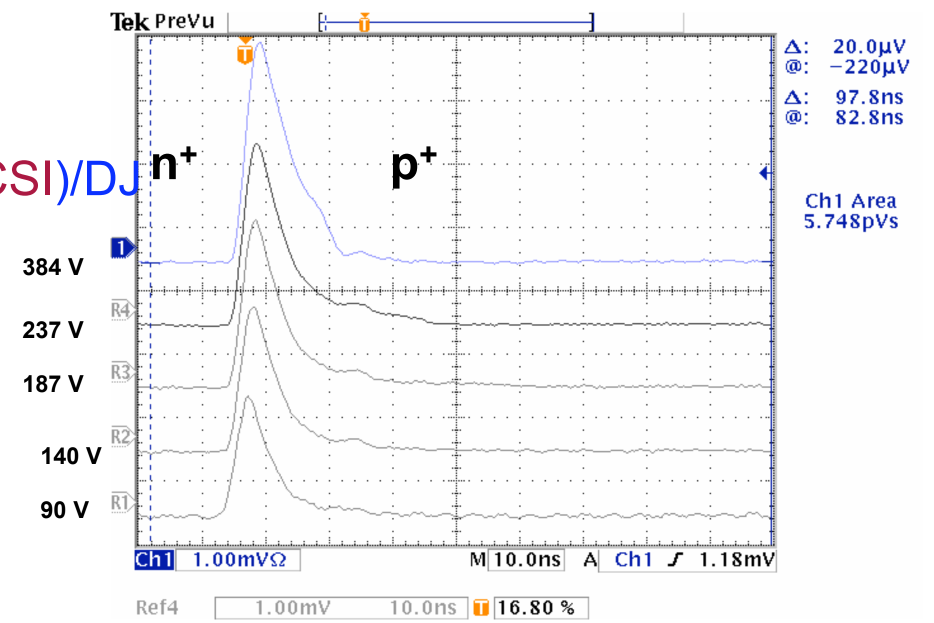
Double junction, and SCSI seen



-SC (SCSI)/DJ

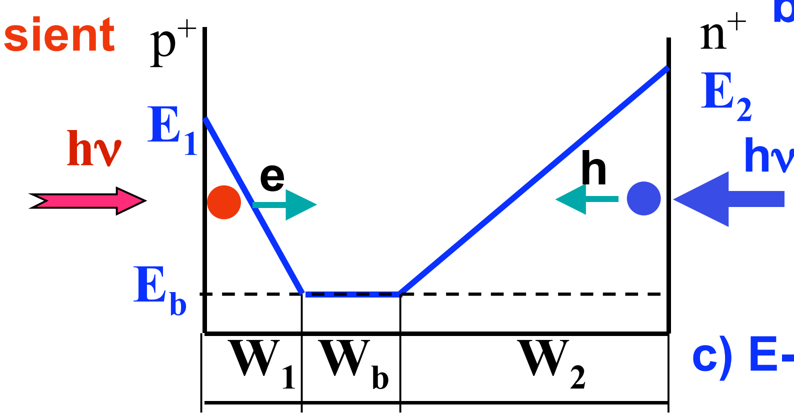
1480-13, $1.5 \times 10^{14}\ n/cm^2$, (22 d RT anneal) MCZ n-type Si, $p^+/n/n^+$ structure

Laser back, hole current from n^+ to p^+



a) Electron transient

b) Hole transient



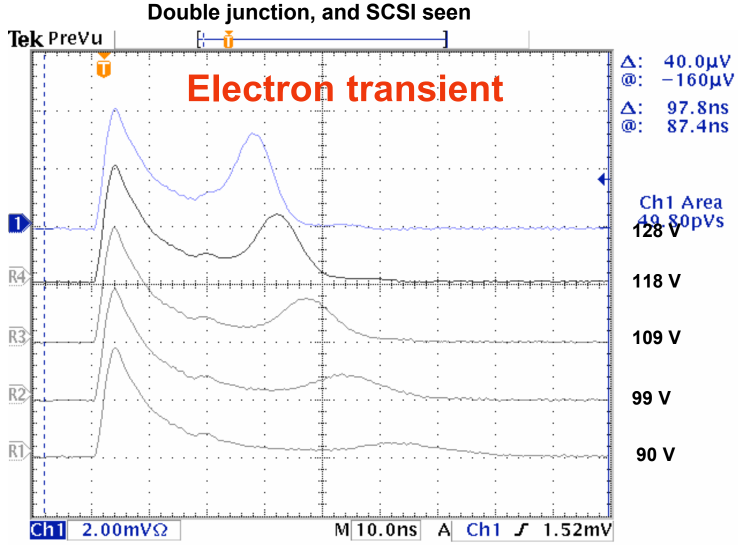
c) E-field profile

Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and beneficial anneal

$1.5 \times 10^{14}\ n_{eq}/cm^2$

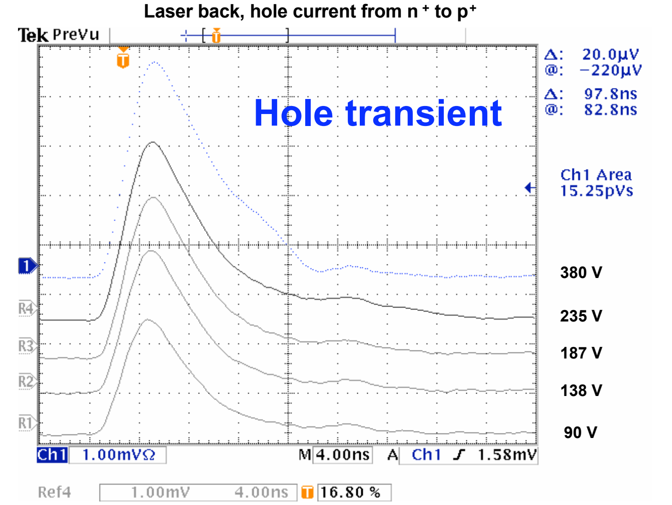
1480-5, 1.5×10^{14} n/cm^2 (22 d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen

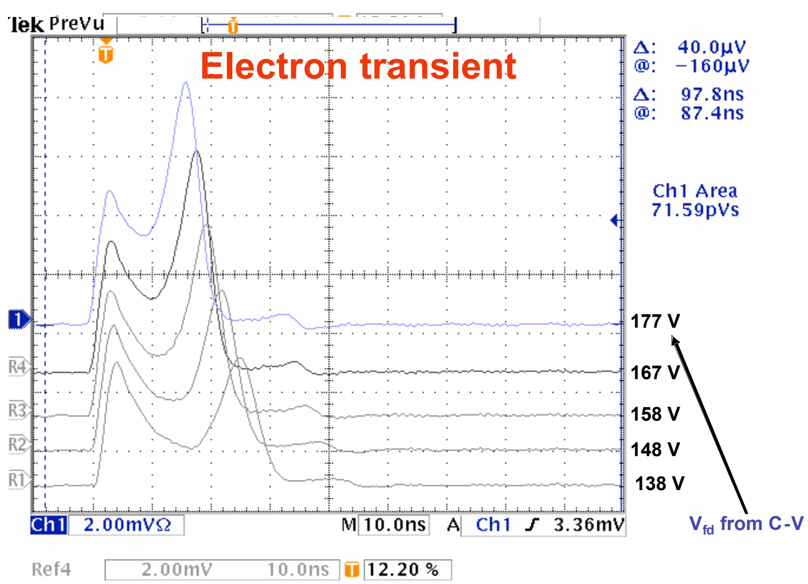


1480-5, 1.5×10^{14} n/cm^2 (22 d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

Laser back, hole current from n^+ to p^+

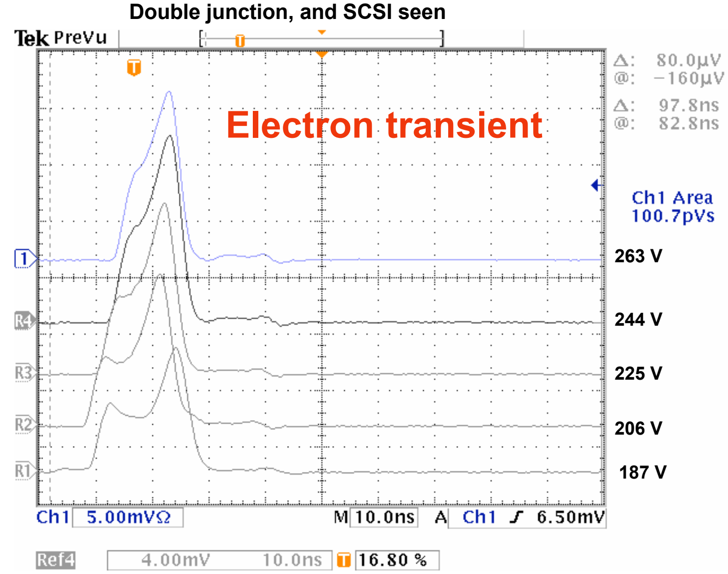


-SC (SCSI)/DJ



1480-5, 1.5×10^{14} n/cm^2 (22 d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen

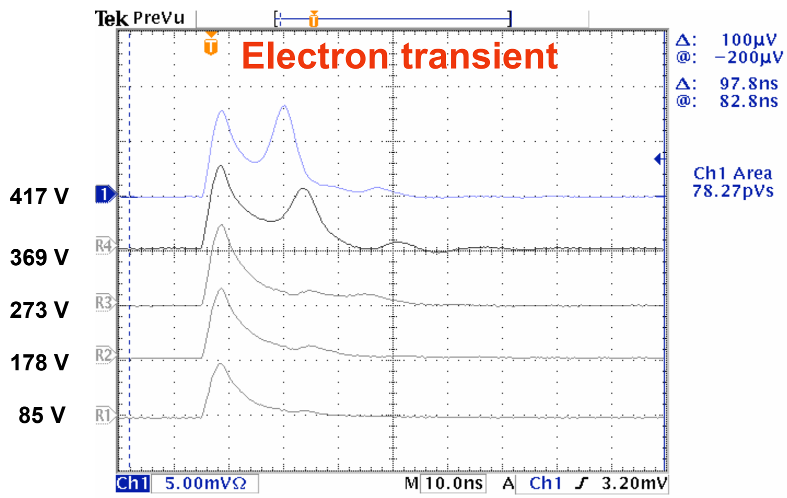


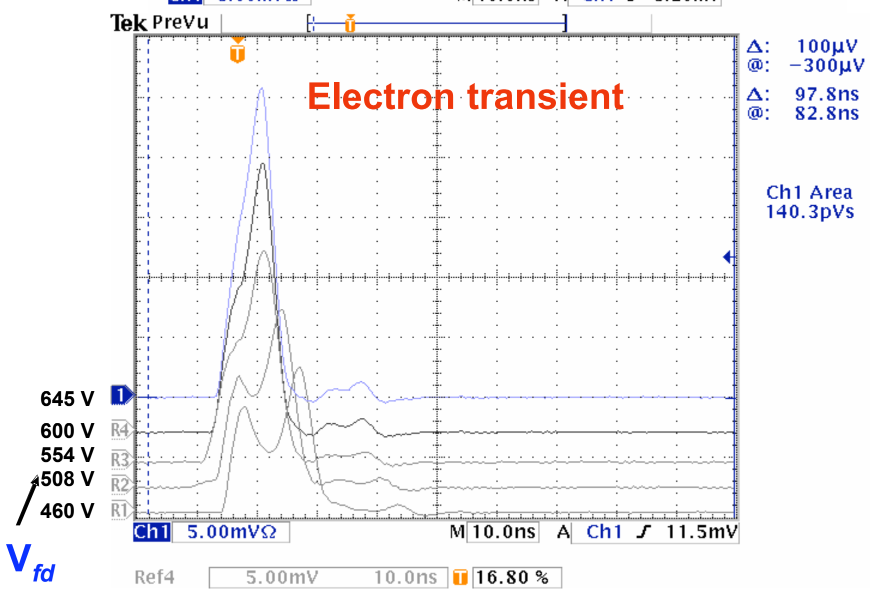
$3x10^{14}$ n_{eq}/cm^2

Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and beneficial anneal

1480-16, $3x10^{14}$ n/cm^2 (22d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

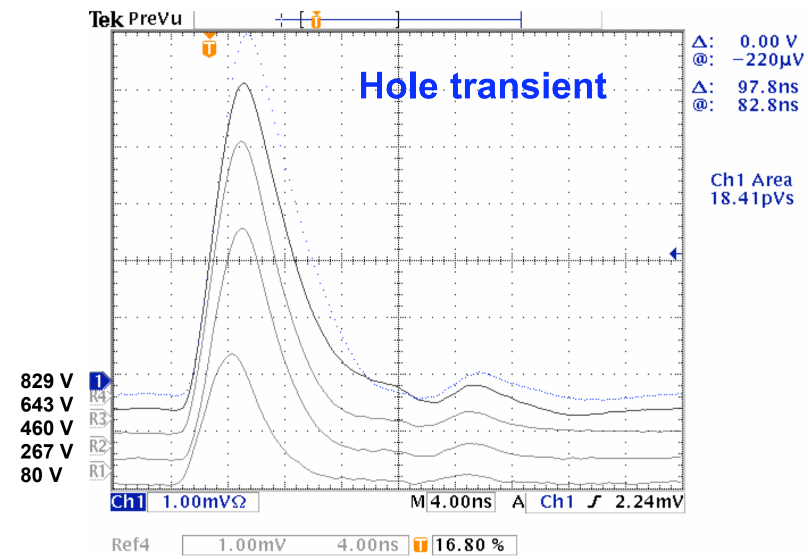
Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen





1480-16, $3x10^{14}$ n/cm^2 (22 d RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure

Laser back, hole current from n^+ to p^+

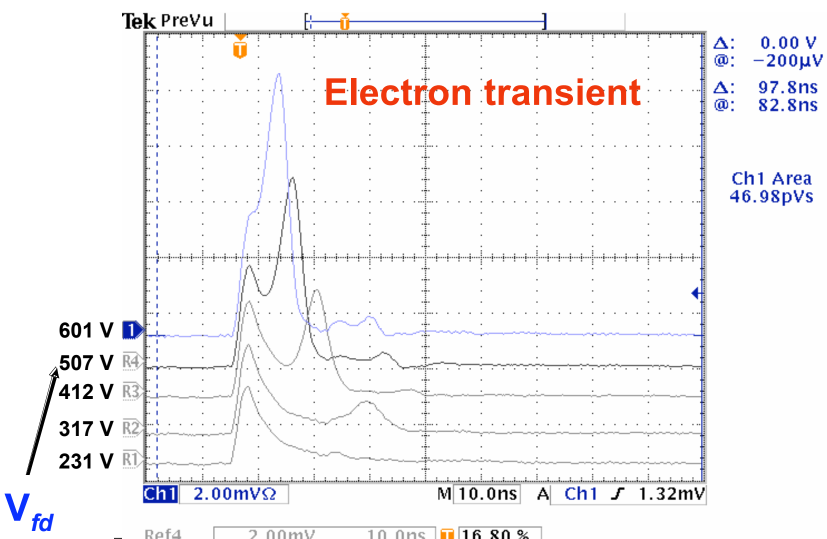


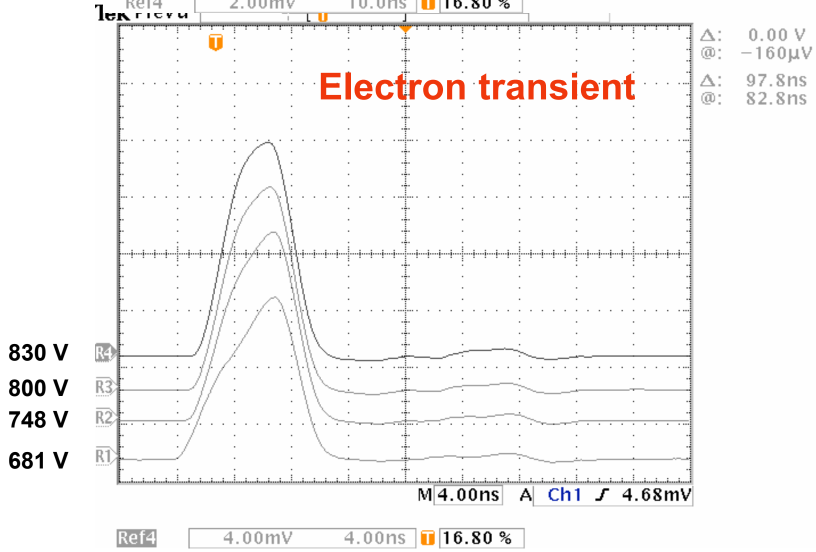
3x10^{14} n_{eq}/cm^2

Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and beneficial anneal

1480-14, 3x10^{14} n/cm^2 (22d RT anneal), MCZ n-type Si, p$^+$/n/n$^+$ structure

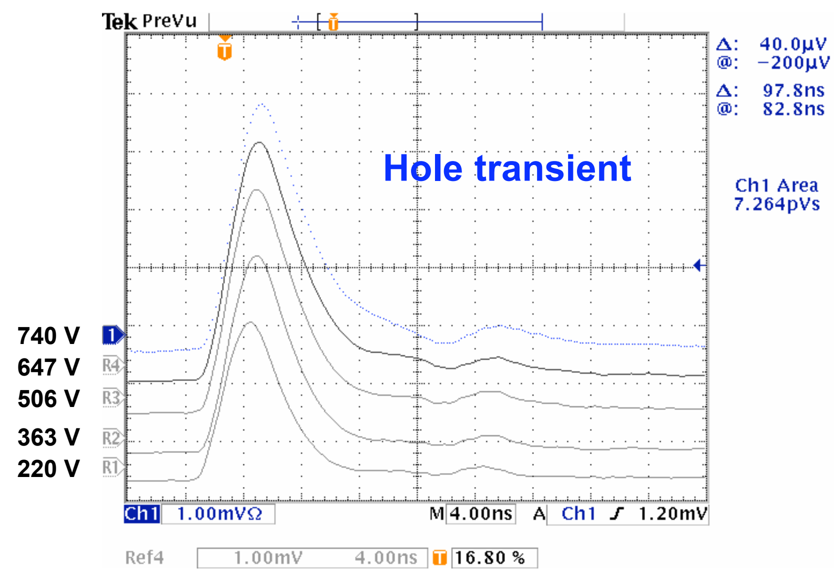
Laser front, electron current from p$^+$ to n$^+$
Double junction, and SCSI seen





1480-14, 3x10^{14} n/cm^2 (22 d RT anneal), MCZ n-type Si, p$^+$/n/n$^+$ structure

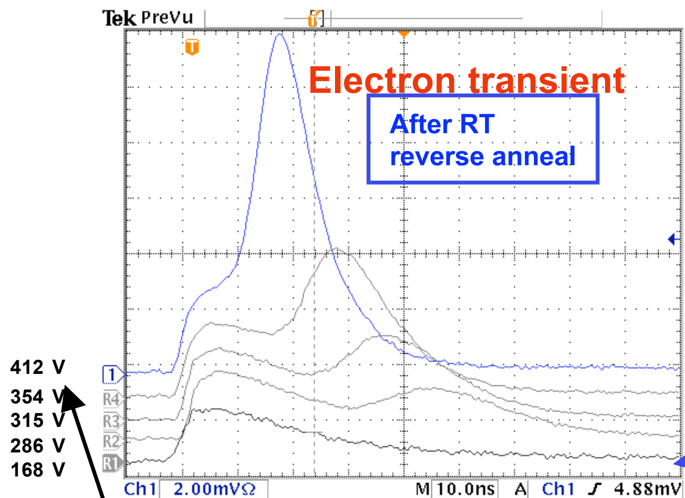
Laser back, hole current from n$^+$ to p$^+$



Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and 5.5-month RT reverse anneal:
a) no gamma radiation during the anneal (control)

1480-13, 1.5×10^{14} n/cm^2 (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen



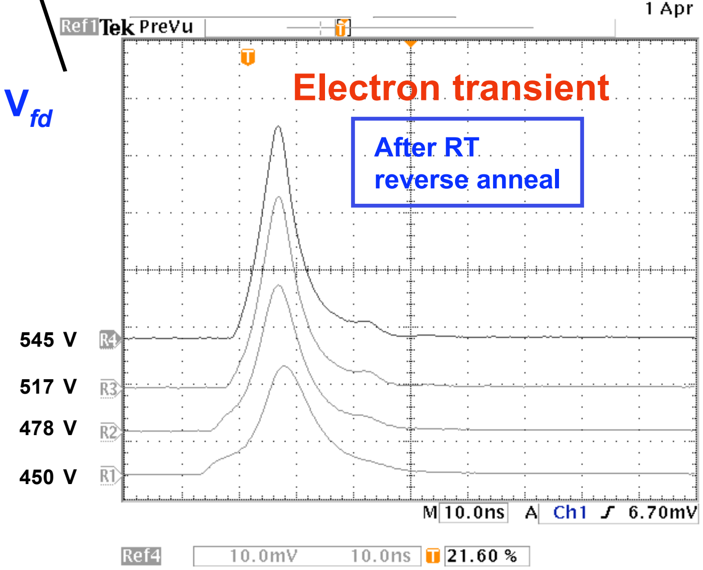
1.5×10^{14} n_{eq}/cm^2

Ch1 Area
365.7pVs

5.5 month RT reverse anneal causes V_{fd} Increases from 187 V to about 400 V

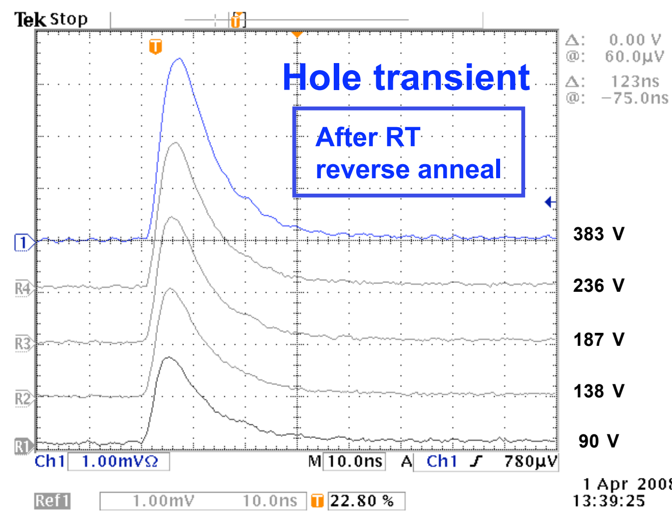
1 Apr 2008

V_{fd}



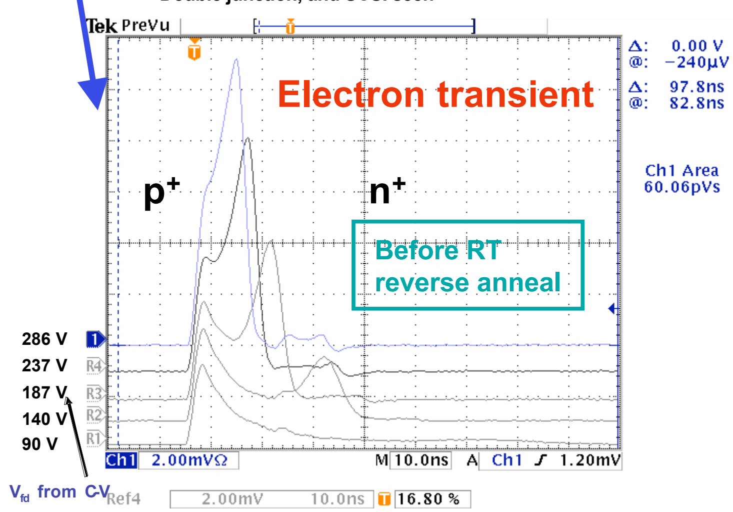
1480-13, 1.5×10^{14} n/cm^2 (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

Laser back, hole current from n^+ to p^+
Double junction, and SCSI seen



1480-13, 1.5×10^{14} n/cm^2 (22 d RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

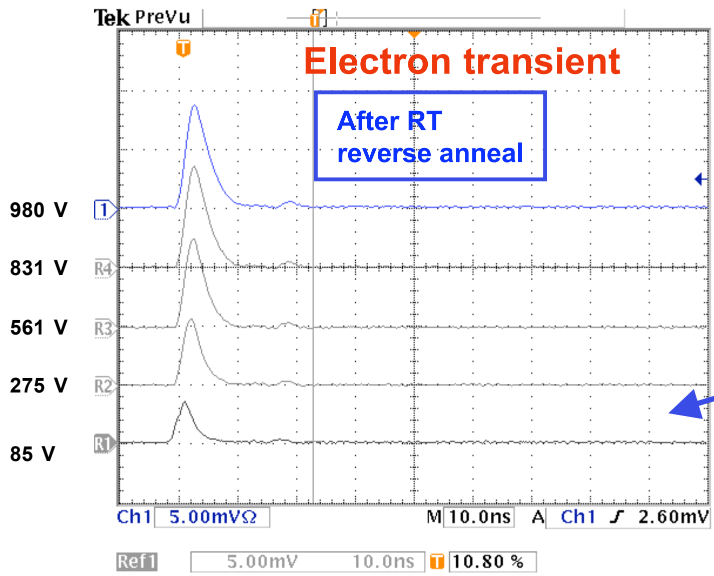
Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen



Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and 5.5-month RT reverse anneal: a) no gamma radiation during the anneal (control)

1480-14, 3x10^{14} n/cm^2 (5.5 month RT anneal), MCZ n -type Si, p$^+$/n/n$^+$ structure

Laser front, electron current from p$^+$ to n$^+$
Double junction, and SCSI seen (V_{fd}>1000V)



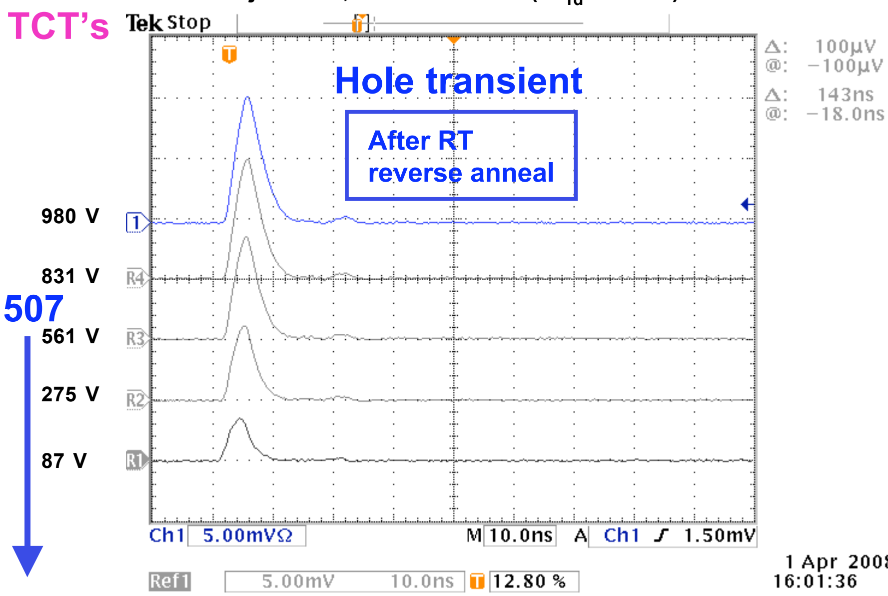
$3x10^{14}$ n_{eq}/cm^2

Symmetrical TCT's

5.5 month RT reverse anneal causes V_{fd} Increases from 507 V to >1000 V

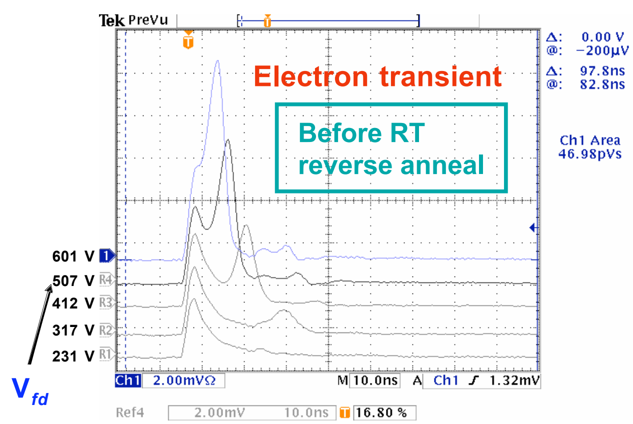
1480-14, 3x10^{14} n/cm^2 (5.5 month RT anneal), MCZ n -type Si, p$^+$/n/n$^+$ structur

Laser back, hole current from n$^+$ to p$^+$
Double junction, and SCSI seen (V_{fd}>1000V)



1480-14, 3x10^{14} n/cm^2 (22d RT anneal), MCZ n -type Si, p$^+$/n/n$^+$ structure

Laser front, electron current from p$^+$ to n$^+$
Double junction, and SCSI seen



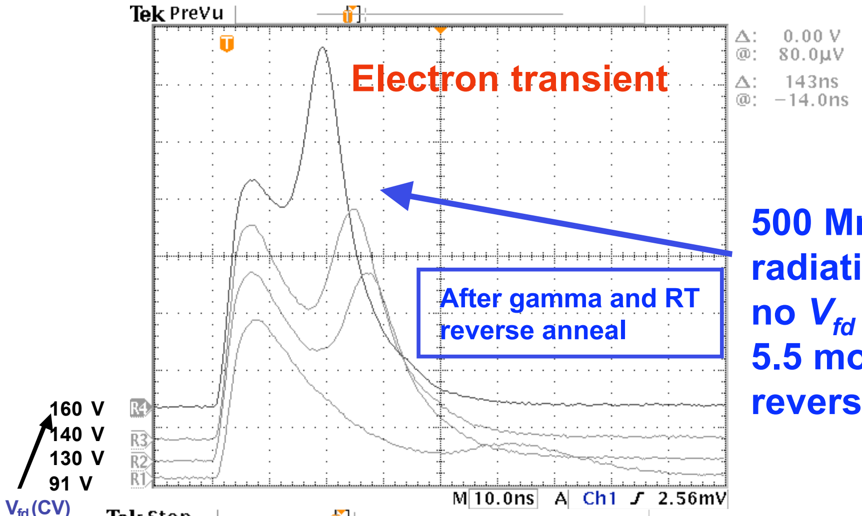
Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and 5.5-month RT reverse anneal: b) with gamma radiation during the anneal

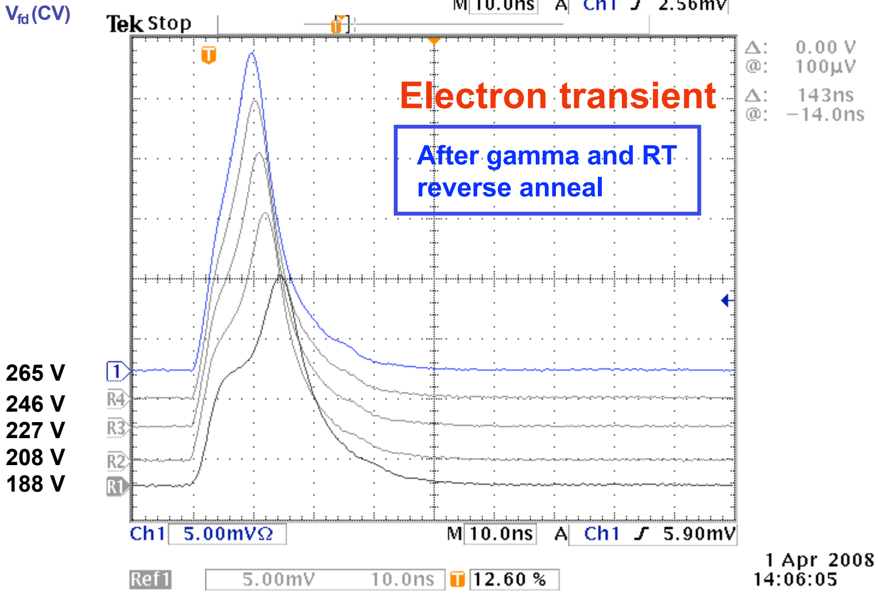
1480-5, 1.5×10^{14} n/cm^2 +500 Mrad gamma (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+

Double junction, and SCSI seen

1.5×10^{14} n_{eq}/cm^2



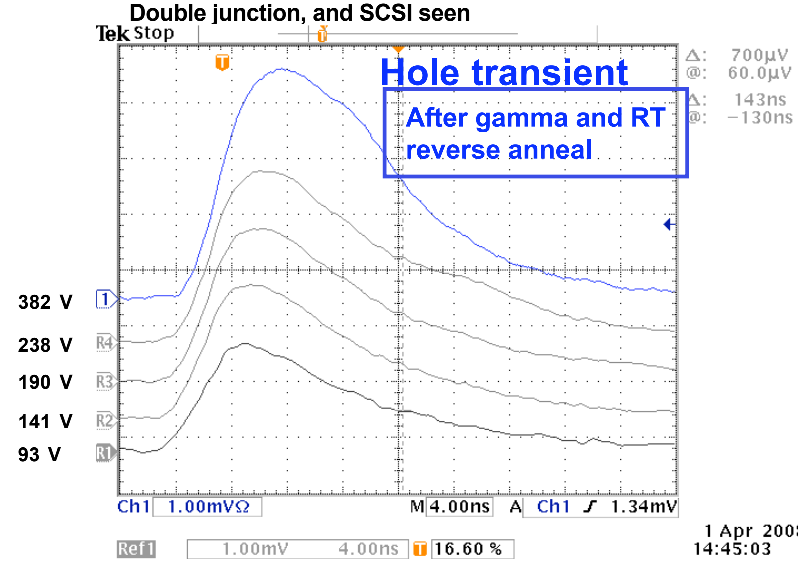


500 Mrad gamma radiation causes no V_{fd} Increases in 5.5 month RT reverse anneal !

1480-5, 1.5×10^{14} n/cm^2 +500 Mrad gamma (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

Laser back, hole current from n^+ to p^+

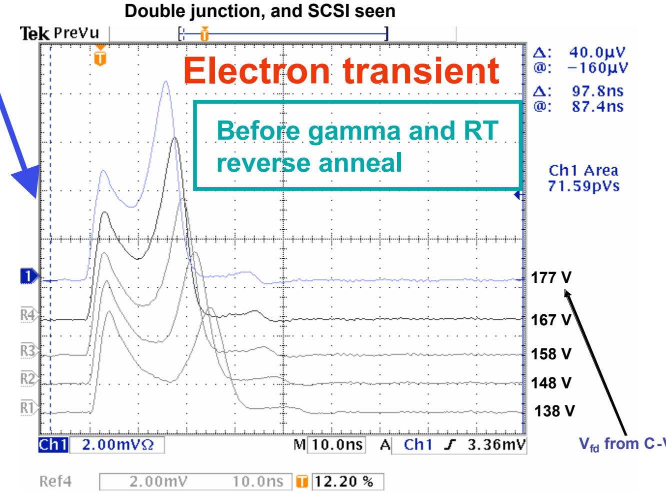
Double junction, and SCSI seen



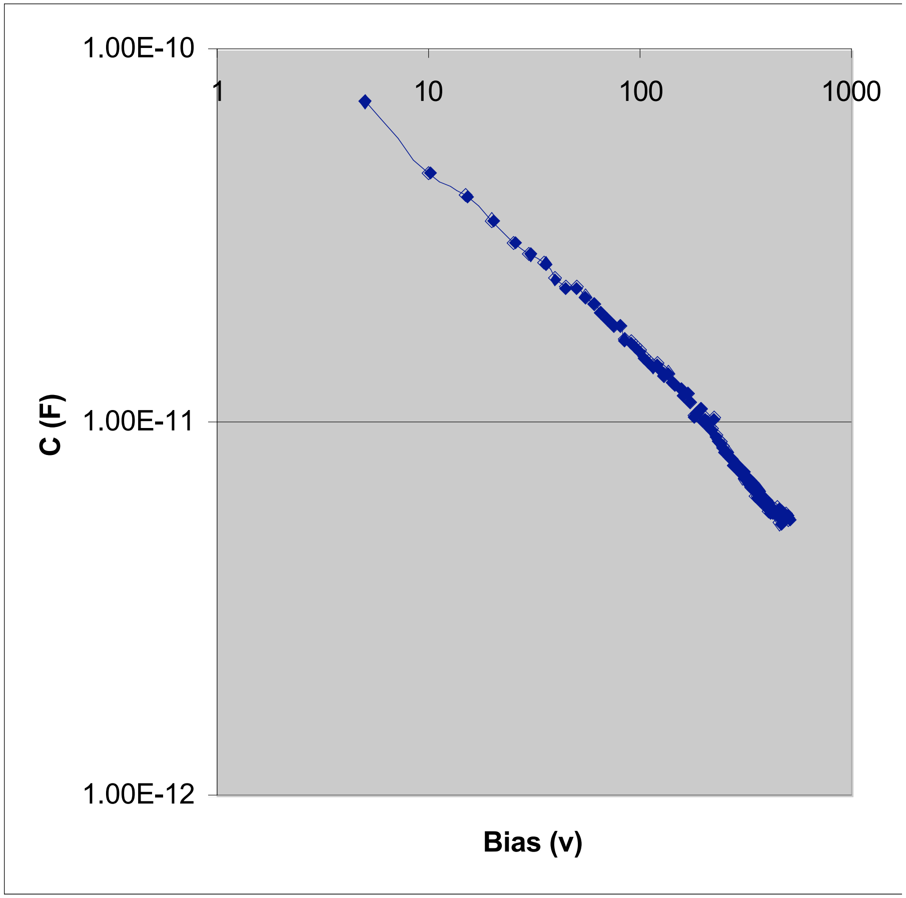
1480-5, 1.5×10^{14} n/cm^2 (22 d RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure

Laser front, electron current from p^+ to n^+

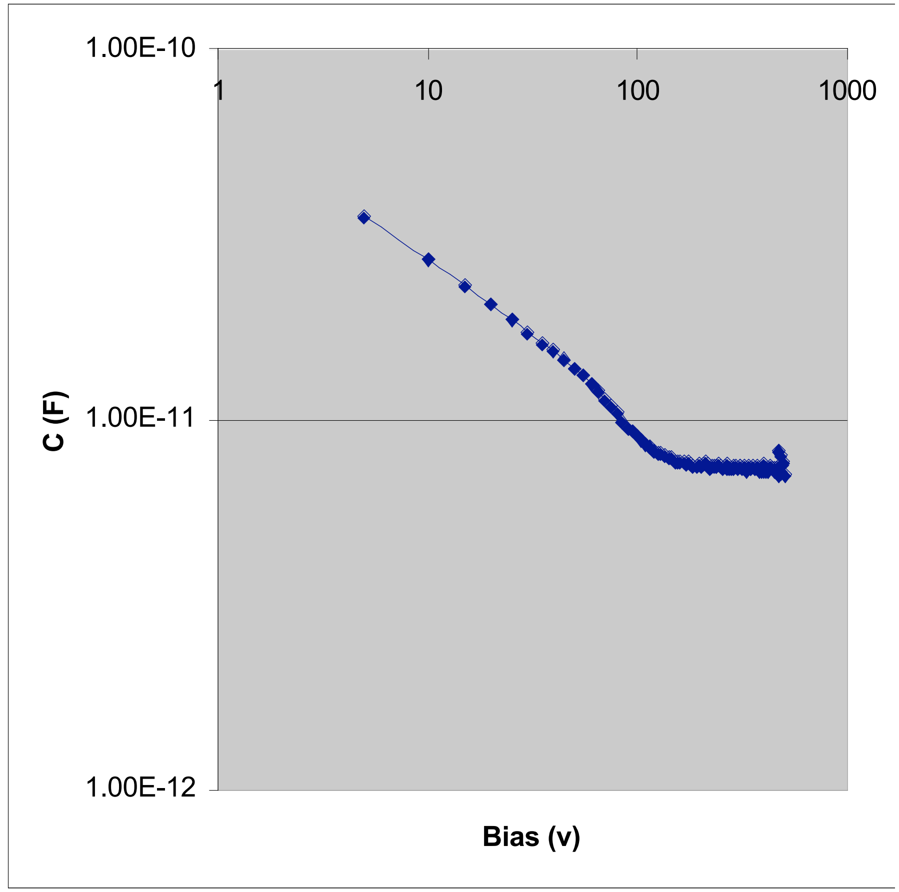
Double junction, and SCSI seen



1480-13, 1.5×10^{14} n/cm^2 (5.5 month RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure



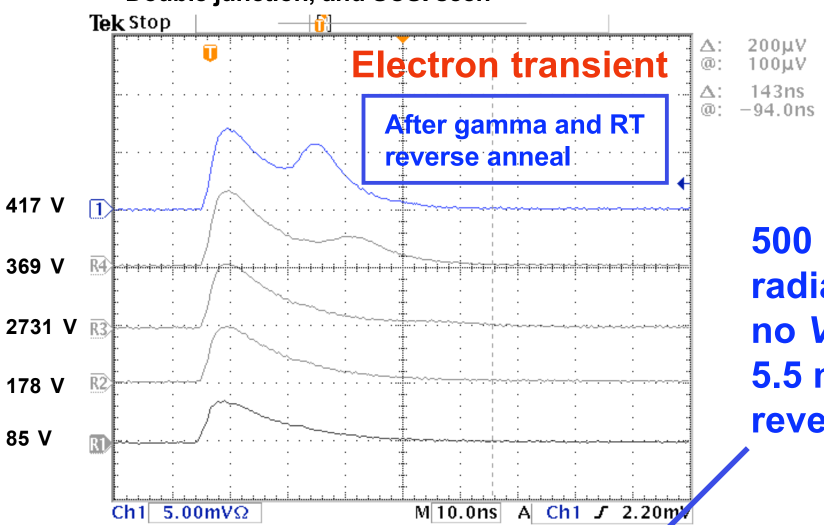
1480-5, 1.5×10^{14} n/cm^2 +500 Mrad gamma (5.5 month RT anneal), MCZ n-type Si, $p^+/n/n^+$ structure



CV data confirms that 500 Mrad gamma radiation suppresses/compensates the RT reverse annealing

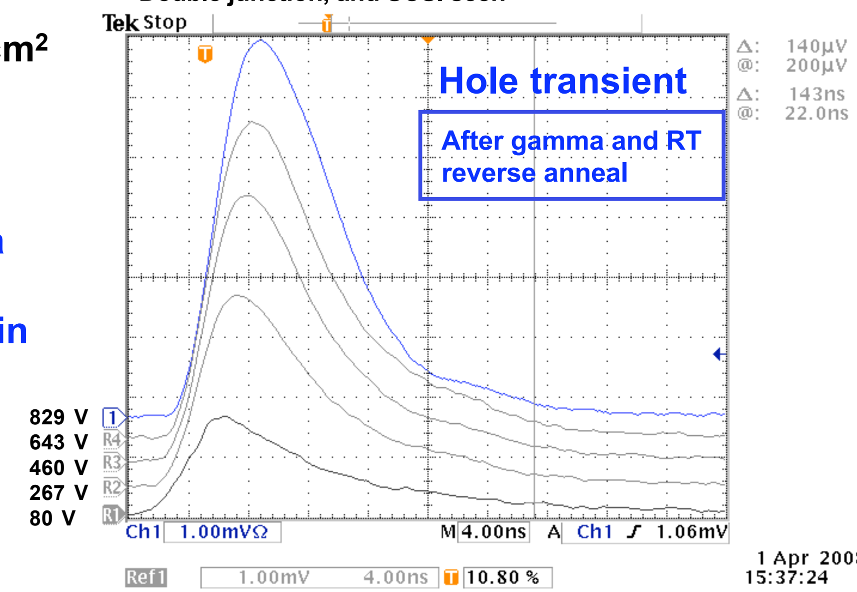
Experimental results of TCT current pulse shapes on samples after 1 MeV neutron irradiation and 5.5-month RT reverse anneal: b) with gamma radiation during the anneal

1480-16, 3×10^{14} n/cm^2 +500 Mrad gamma (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure
Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen

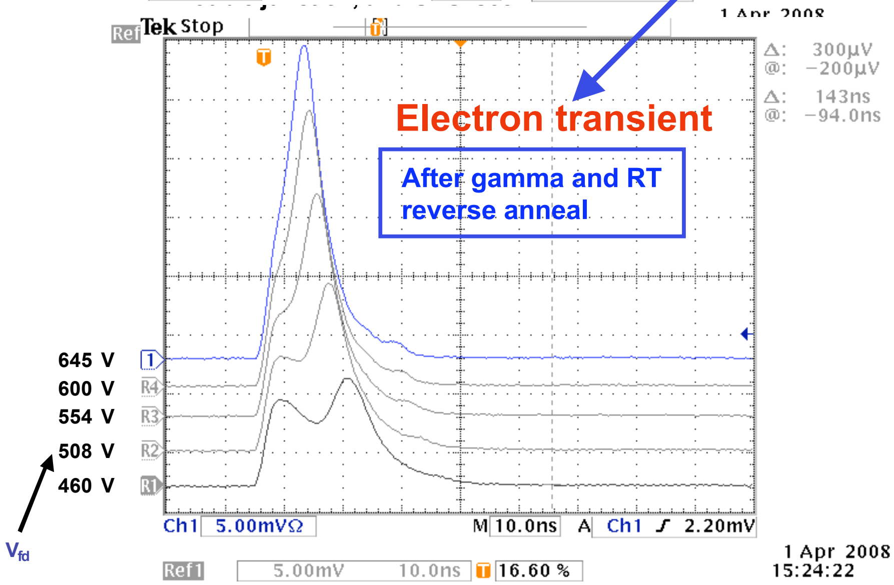


3×10^{14} n_{eq}/cm^2

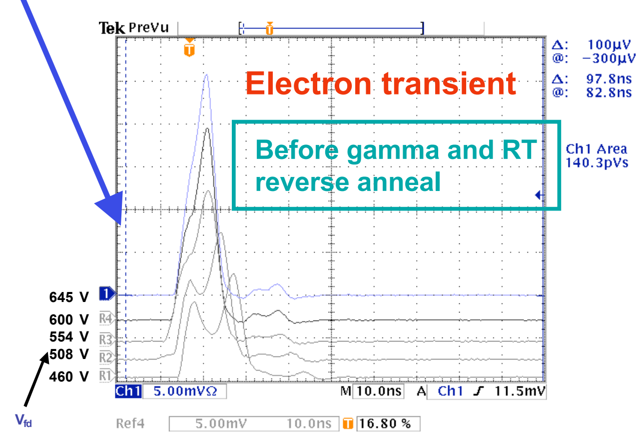
1480-16, 3×10^{14} n/cm^2 +500 Mrad gamma (5.5 month RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure
Laser back, hole current from n^+ to p^+
Double junction, and SCSI seen



500 Mrad gamma radiation causes no V_{fd} Increases in 5.5 month RT reverse anneal !



1480-16, 3×10^{14} n/cm^2 (22d RT anneal), MCZ n -type Si, $p^+/n/n^+$ structure
Laser front, electron current from p^+ to n^+
Double junction, and SCSI seen



Discussion

Table I Voltage at the equal double peak (V_{DP}), full depletion voltage (V_{fd}), and N_{eff} for n -type MCZ Si detectors after neutron and gamma irradiations and RT anneal . Before any irradiation, V_{fd0} = 350V, N_{eff0} =2.88x10^{12}/cm^3. Negative sign in N_{eff} means negative space charge (-SC).

Sample #	Neutron Fluence (n_{eq}/cm^2)	Gamma Dose After n irrad., During 5.5 months RT anneal (Mrad)	As Irradiated 6.6 hours RT Anneal			22 Days RT Anneal			5.5 months RT Anneal		
			V_{DP} (V)	V_{fd} (V)	N_{eff} (cm^{-3})	V_{DP} (V)	V_{fd} (V)	N_{eff} (cm^{-3})	V_{DP} (V)	V_{fd} (V)	N_{eff} (cm^{-3})
1480-5	1.5x10^{14}	500	227	276	-2.3x10^{12}	138	177	-1.5x10^{12}	130	170	-1.4x10^{12}
1480-13	1.5x10^{14}	0	227	275	-2.3x10^{12}	150	187	-1.5x10^{12}	354	400	-3.3x10^{12}
1480-15	3x10^{14}	0	-	-	-	412	507	-4.2x10^{12}	>1000	>1100	-8.9x10^{12}
1480-16	3x10^{14}	500	612	782	-	417	508	-4.2x10^{12}	440	508	-4.2x10^{12}

Red : Reverse anneal **GREEN: Reverse anneal suppression/compensation**

The reverse annealing in samples irradiated by gamma at 500 Mrad is completely suppressed, regardless of the neutron fluence!

Discussion

Table II Changes in N_{eff} during the 5.5 month RT anneal.

Neutron Fluence (n_{eq}/cm^2)	Gamma dose after n-rad,, during the 5.5 month anneal (Mrad)	Changes in N_{eff} during the 5.5 month anneal (Mrad) (cm^{-3})	Reverse annealing suppression	+SC would have been generated with gamma rad. alone
$1.5\text{x}10^{14}$	500	$+0.1\text{x}10^{12}$	Completely	$+1.5\text{x}10^{12}$
$3.0\text{x}10^{14}$	500	~ 0	Completely	$+1.5\text{x}10^{12}$
$1.5\text{x}10^{14}$	0	$-1.8\text{x}10^{12}$	No	-
$3.0\text{x}10^{14}$	0	$-4.7\text{x}10^{12}$	No	-

- The positive space charge created by 500 Mrad gamma radiation would approximately compensate the negative space charge in the sample irradiated by $1.5\text{x}10^{14}$ n_{eq}/cm^2
- But it is too small to do same for the sample irradiated by $3.0\text{x}10^{14}$ n_{eq}/cm^2
- This points to some interaction between defects generated by gamma and that by reverse annealing in n-irradiated samples

Summary

- **SCSI and double peak/double junction in n-irradiated MCZ Si detectors was confirmed**
- **Subsequent gamma irradiation up to 500 Mrad in a 5.5 month period caused complete suppression of the reverse annealing, which happened in control samples (no gamma radiation)**
- **This suppression is independent of the neutron fluence (from 1.5-3.0x10^{14} n_{eq}/cm^2)**
- **This points to some interaction between defects generated by gamma and that by reverse annealing in n-irradiated samples**
- **More systematic studies have been planned to confirm the effect**