Micro Strip Silicon Detectors R&D at Fermilab for the CMS tracker upgrade campaign

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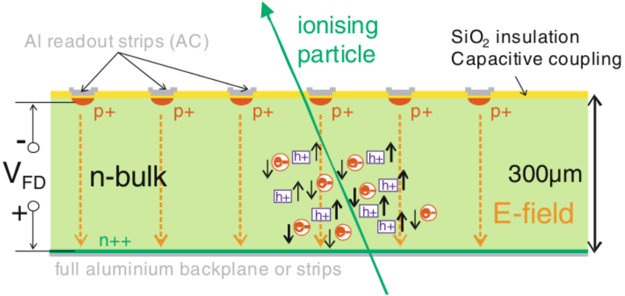
Silicon detectors - basics

- The amount of free charge carriers in standard silicon sensors is 10^5 times higher than the amount of charge carriers generated by a ionizing particle
- Depletion of the p-n junction volume via a reverse-biased configuration: $w = \sqrt{2\,\varepsilon\,\mu\,\rho\,V_{bias}}$, w thickness of the depleted region
- Minimal working point: full depletion voltage V_{fd} such that $w = d$

$$V_{fd} = \frac{d^2}{2\,\mu\,\varepsilon\,\rho}$$

where $\rho = \frac{1}{\mu\, e\, N}$ is the silicon resistivity for a doping concentration N, μ is the pairs mobility and d the thickness of the sensor.



The CMS strip tracker

The CMS strip tracker

- 206 m^2 of active silicon detectors
- 15 to 20 μm resolution from inner to outer layers
- 10^{13} to $5 \cdot 10^{14}$ equivalent 1 MeV neutrons per cm^2 irradiation in 10y of LHC operation

SHLC and the tracker upgrade in 2020

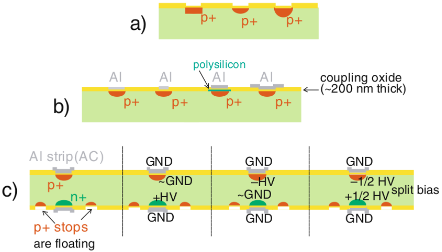
- More radiation hardness is needed - SLHC luminosity will be 5 times greater than the current design luminosity
- Strip occupancy needs to be minimized
- CMS - Hamamatsu Photonics R&D campaign involving a number of CMS Tracker institutes including (but not limited to) Brown, Cantabria, CERN, Florence, FNAL, Hamburg, Karlsruhe, Louvain, Montpellier
- Prototype wafers are built in Japan and sent to the labs for testing, irradiation and annealing

Standard quality assurance tests for strips detectors

- Global current-voltage characteristic (IV)
- Full capacitance-voltage ramps (CV), to determine V_{fd} (full depletion voltage)
- Strip parameters - e.g. bias resistance, coupling capacitance, strip-to-bulk capacitance, interstrip capacitance

Strip implants

p^+ doped silicon implants on n-type bulk (or vice versa). A readout aluminum strip, separated by a thin layer of SiO_2, overhangs every implant. These capacitors a/c-couple the implant signal to the amplifier. Additional disconnected n^+ (p^+) implants may be laid floating between the strips to increase segmentation.



Different strip designs

Load capacitance

Coupling capacitance C_C

- Measured between implant and aluminum strip (implant to readout electronics capacitance)
- $C_C \propto$ signal: it should be maximized
- Large C_C means thin SiO_2 isolation layer
- Risk to crate a pinhole (short between implant and aluminum)
- Typical values: 300 to 600 pF per strip
- Typical parasitic capacitance for CMS sensors: 1.2 pF/cm

Parasitic capacitance

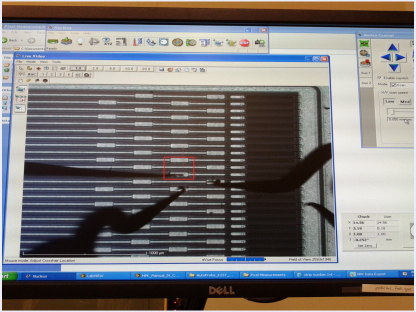
All of the parasitic capacitances should be minimized to maximize signal-to-noise ratio.

- Interstrip capacitance C_{int}: it increases with the strips density (= resolution); it decreases with strip width.
- Backplane capacitance C_b: measured between each strip and the backplane, where the bias voltage is applied. For CV ramps we probe the capacitance between the bias ring, connected to all the strips of a region), and the backplane: $C_b \approx C_{meas}/N_{strips}$

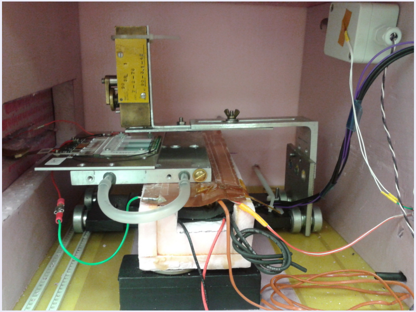
Test stations at SiDet labD, Fermilab

- probe stations: automatic and manual
- β-source, laser and cosmic rays trigger and DAQ stations
- cooling systems for the β-source station and the automatic probe station
- dry and cold boxes for items storage

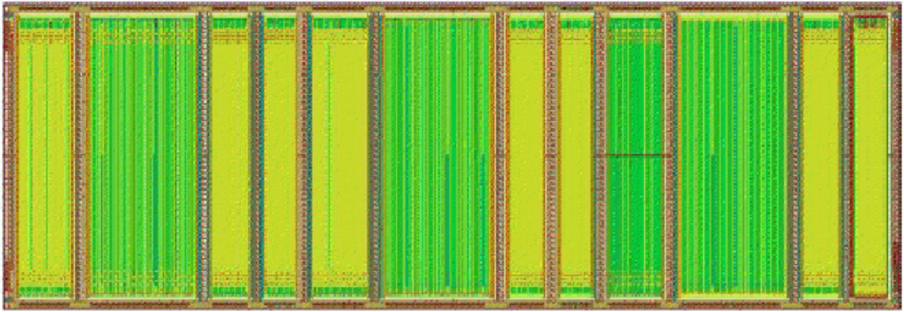
Automatic probe station



Source station



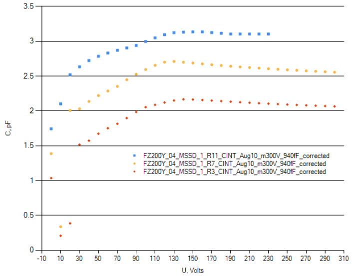
The test MSSDs

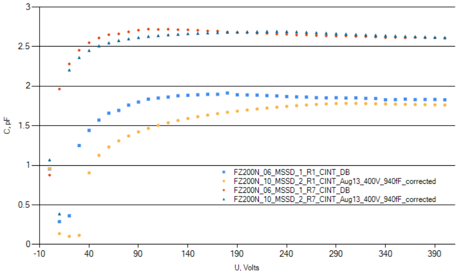


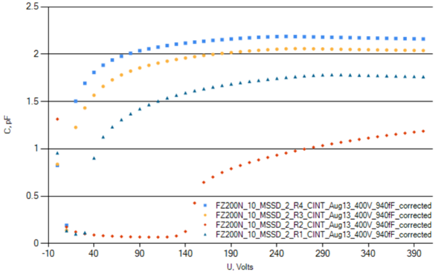
Region	1	2	3	4	5	6	7	8	9	10	11	12
Strip width (μm)	16	34	10	8.5	28	58	18	15.5	40	82	26	22.5
Strip pitch (μm)	120	240	80	70	120	240	80	70	120	240	80	70
Al (μm)	29	47	23	21.5	41	71	31	28.5	53	95	39	35.5
Al/W	1.81	1.38	2.30	2.53	1.46	1.22	1.72	1.84	1.33	1.16	1.50	1.56
W/P	0.13	0.14	0.13	0.12	0.23	0.24	0.23	0.22	0.33	0.34	0.33	0.32

Interstrip capacitance measurements

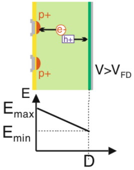
- One week data taking (6 sensors)
- The capacitance is measured between a strip and two neighbours
- General agreement with previous data
- C_{int} increases with the strips width
- C_{int} decreases with the strips pitch







Leakage current



If the bias voltage is raised over V_{FD}, thermally generated pairs begin to be pulled out of the depleted region, giving a reverse current I_{leak} proportional to the dopant concentration ($\simeq$ charge carriers concentration) n_i.

The charge carriers densities at the termal equilibrium are given by:

$$n \propto e^{-\frac{E_C - E_f}{kT}} \text{ (electrons)}$$

$$p \propto e^{-\frac{E_f - E_V}{kT}} \text{ (holes)}$$

where E_C is the energy of the condution band, E_V that of the valence band and E_f is the Fermi energy.

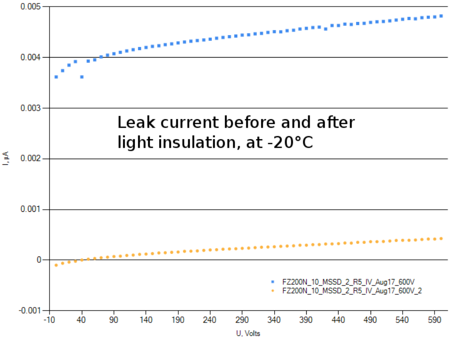
Mass Action Law

$$n \cdot p \equiv n_i^2 \propto e^{-\frac{\Delta E}{kT}} \text{ with } \Delta E \equiv E_C - E_V \quad \Longrightarrow \quad n_i \propto e^{-\frac{\Delta E}{2kT}}$$

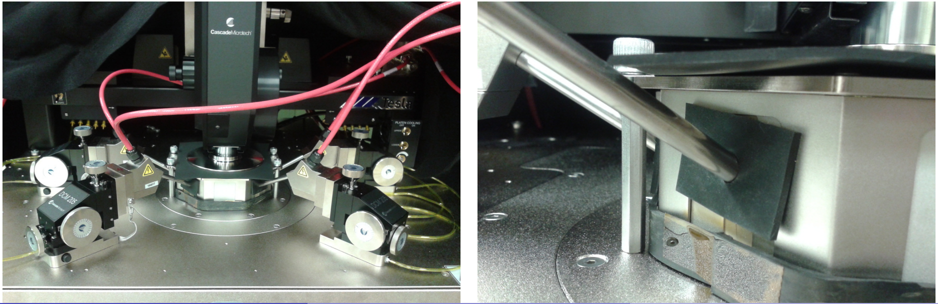
A decrease of 7°C in temperature results approximately in a factor 2 of leakage current reduction.

CV and IV measurements

- Added light insulation to the automatic probe station
- Three weeks data taking (13 sensors)
- Tests performed at -20°C: I_{leak} should fall by a factor 2^5 to 2^6

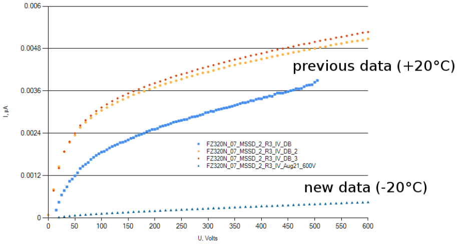


Leak current before and after light insulation, at -20°C



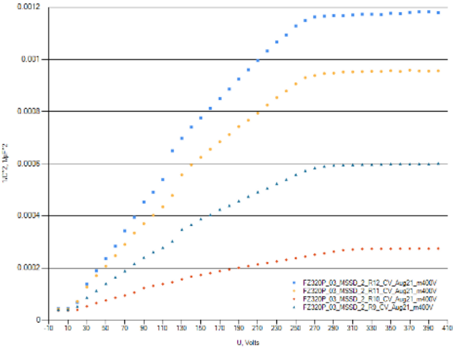
CV and IV measurements

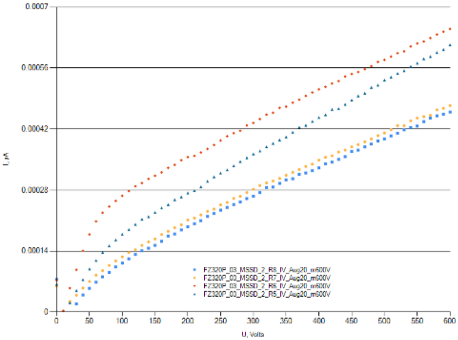
- Room temperature to cold I_{leak} observed factor: $\frac{I_{+20^\circ}}{I_{-20^\circ}} \simeq 30$
- Larger strips draw more current
- Larger regions feature larger capacitance
- $1/C^2$ vs V curves are used to determine V_{fd}



previous data (+20°C)

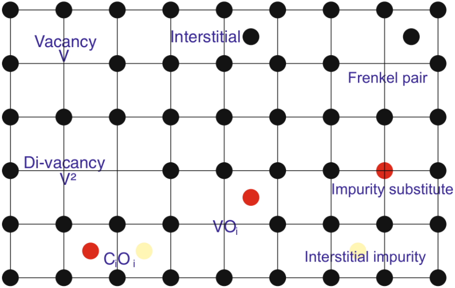
new data (-20°C)





Irradiation

- Nine IV-, CV- and source-measured sensors on shipment to Los Alamos National Lab (LANL) for proton irradiation
- Tests will be repeated after irradiation
- Four irradiated sensors received from CERN ($8 \cdot 10^{14}$ p + $5 \cdot 10^{14}$ n)



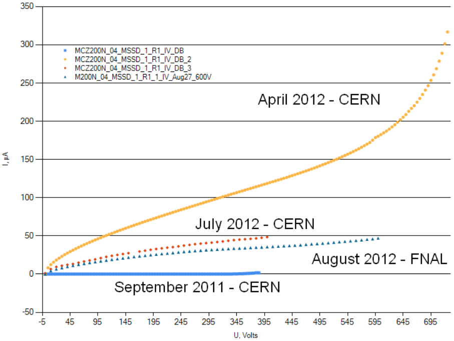
Radiation damage

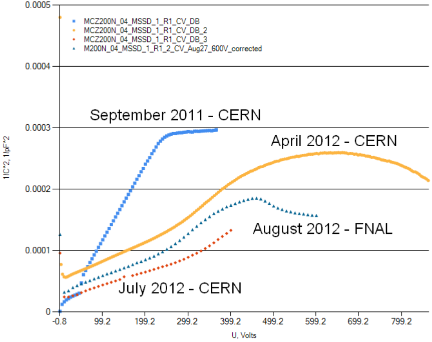
Atoms may be displaced from their lattice positions, and subsequently diffuse. The creation of interstitials and vacancies (space charge) leads to:

- increase of I_{leak} due to the creation of additional energy levels
- increase of the voltage needed to transport charges through the full sensor thickness: $V_{fd} = \frac{e}{2\,\varepsilon}\,|N_{eff}|\,d^2$, where N_{eff} is the effective doping level
- the defects in the lattice may act as traps for charged particles: decrease in collection efficiency. At effecting fluences above 10^{15} equivalent 1 MeV neutrons per cm^2, charges may no longer arrive at the collecting electrodes in 300 μm thick sensors.

Irradiated sensors IV and V_{fd}

- Irradiated sensors are stored at -20°C to avoid unintended annealing $\Longrightarrow$ need to warm them up in a dry box before inserting them in the probe station, to prevent moisture from affecting the measurements
- After irradiation the leakage current is much greater than before, as expected
- The depletion voltage is no more well-defined, e.g. for a 200 μm thick $n-$type sensor it increased from $\sim$ 200 V to $\sim$ 650 V
- Room temperature annealing during beam test and shipment to Fermilab: V_{fd} decreased to $\sim$ 380 V





Annealing

Heating up irradiated sensors may lead to two consequences:

- Fixing lattice defects by letting them decay or recombine with free charge carriers: **beneficial annealing**. Possibility of:
  - Frenkel pair recombination ($I + Si_V \rightarrow Si$)
  - vacancy and interstitial combination (e.g $V + V \rightarrow V^2$)
  - combination of more complex defects

  Recovery from the change in space charge described by an exponential form:

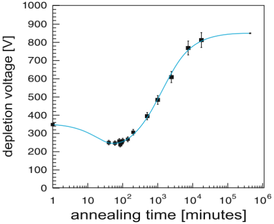
  $$N_a(t) \propto \Phi \, e^{-t/\tau_a}$$

- Creation of new defects because of the heat: **reverse annealing**, described by the form

  $$N_y(t) \propto \Phi \left(1 - \frac{1}{1 + t/\tau_y}\right)$$

Annealing constants for CMS present tracker

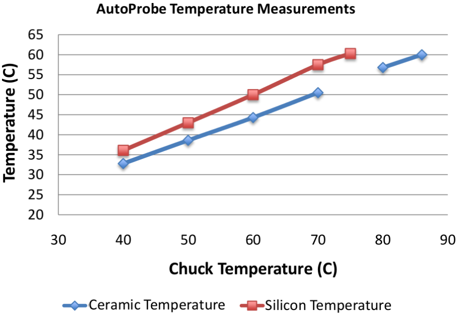
Temperature (°C)	-10	0	20	60
Beneficial annealing	306 d	53 d	55 h	19 min
Reverse annealing	516 y	61 y	475 d	21 h

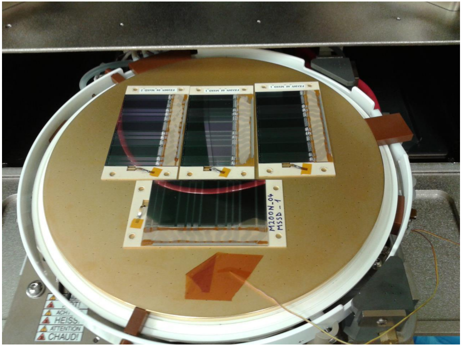


Annealing procedure

To anneal the sensors we used the automatic probe station. The platform temperature can be raised, and the heat will reach the sensor passing through the ceramic holder.

The platform holding the sensors has to be set at 75°C to achieve 60°C on the sensor (characterization performed using a thermo-resistor and a test sensor).

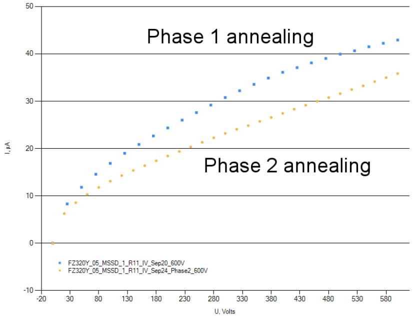


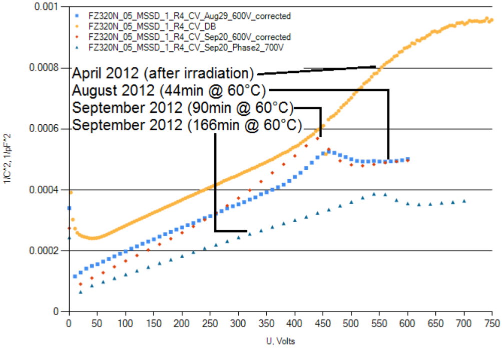


Annealing tests

One week of work (4 sensors annealed and IV- and CV-tested).

- **Before annealing:** 128 hours at room temperature accumulated during test beam and shipment to Fermilab, equivalent to 44 minutes @ 60°C cumulative
- **Phase 1 annealing:** 90 minutes @ 60°C cumulative
- **Phase 2 annealing:** 166 minutes @ 60°C cumulative





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Thank you for your attention