2nd DRD3 Collaboration Week – Radiation Damage Working Group

Geneva, 4th December 2024

Defect Assisted Research for Dark Matter Applications (D.A.R.M.A.)

Evangelos – Leonidas Gkougkousis[1], Ioana Pintilie[2], Andrei Nitescu[2], Ben Kilminster[1]

1: University of Zurich
2: NIMP - Bucharest

•Overview

Introduction

Dark Matter
Skipper CCDs

Deep Level
Transient
Spectroscopy

Experimental
Setup

Conclusion

- Introduction
  - Silicon Lattice Overview
  - Introduction to Lattice Defects
  - Defects as tools is Physics (V-N Defect, Dark matter detection)
- Skipper CCDs & Dark Matter
  - What is Dark Matter?
  - Challenges in direct detection experiments
  - Skipper CCDs and their use as dark matter detectors
- Deep Level Transient Spectroscopy
  - Principles and Methodology
  - Integration with Skipper CCDs
  - Charge Injection & Lock-In Amplifiers
- Experimental Setup and Results
  - Overview and Current Status
  - Initial results on test diodes
  - Integration with test CCDs
- Conclusions

•Introduction

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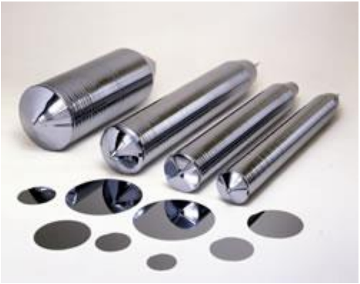
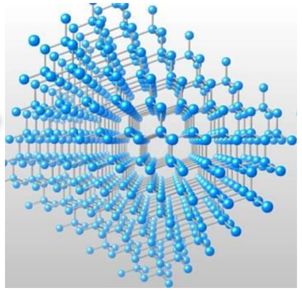
Silicon Lattice Overview

FZ, CZ, MCz

Crystallization process





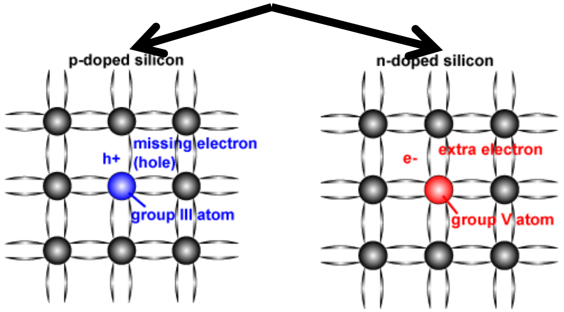
- Silicon 2nd most abundant element
- 28 % per weight of earths crust

Wafer level monocrystals (100, 111 orientations **ONLY**)

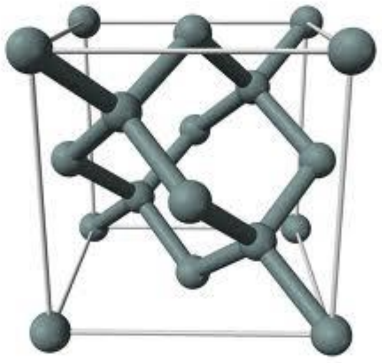
Pure silicon lattice

Si Parameters Table	
Atomic displacement	15 – 35 eV (direction dependent, 35 @ 111)
Density	2.33 gr/cm^3 0.5 x 10^{23} at./cm^3
Lattice constant	5.43 x 10^{-10} m

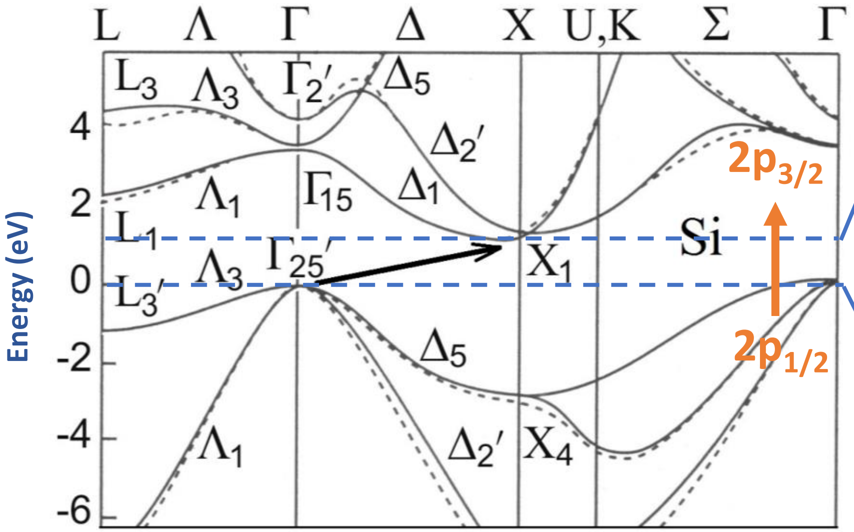
DOPING = Energy Level Shifting

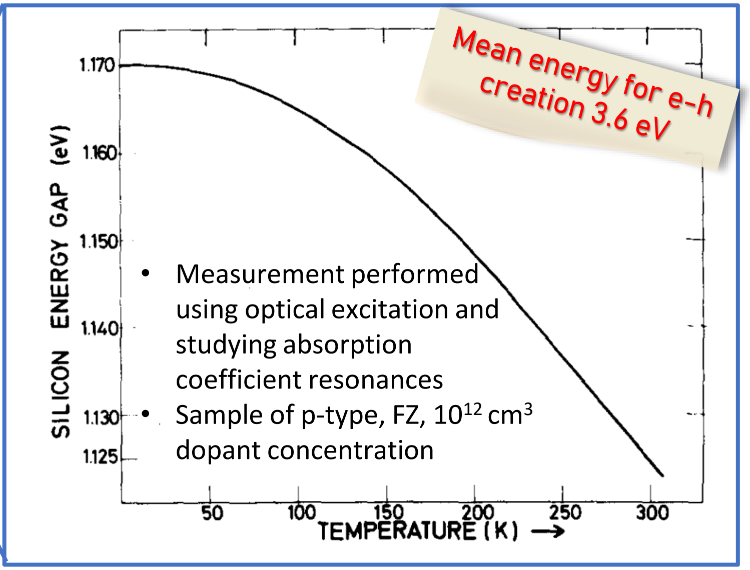


FCC derivative structure with 2-atiom basis tetrahedral arrangement



Indirect Semiconductor – Band Structure





- Measurement performed using optical excitation and studying absorption coefficient resonances
- Sample of p-type, FZ, 10^{12} cm^3 dopant concentration

At 0 K theoretical maximum of 1.1701 eV, drops to 1.1249 eV at 300 K

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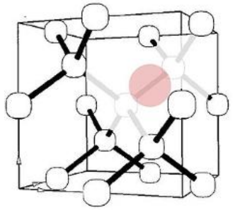
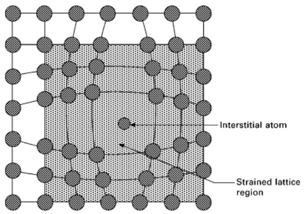
Introduction to Lattice Defects

Vacancy (V): Loss of an atom from normal lattice structure leaving a gap

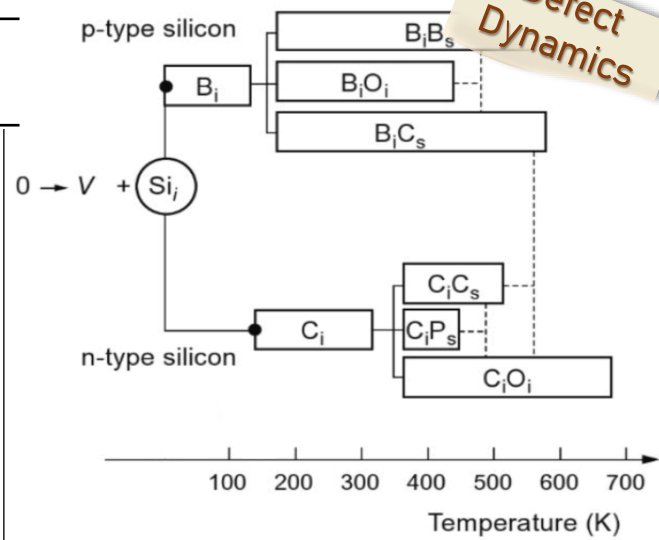


Interstitial (I): The presence of an out-of-lattice atom at a certain position creating strain and deformation



Defect generation energy	
Point Defect	< 25 – 30 eV
Cluster Defect	< 5 keV

Defect Dynamics



Four main disruptive mechanisms:

Substrate

1. **Reduced primary charges induced in substrate** → $^{1}/_{\tau} = \beta \times \Phi$
2. **Acceptor re-introduction rate** → $N_{Act.} = g_A \times \Phi$

The ROSE collaboration

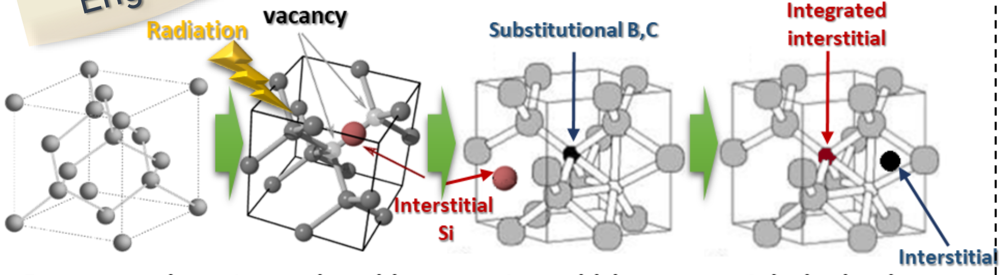
Gain Layer

3. **Reduced active implant through acceptor removal** → $N_{G_\Phi} = f \times N_{G_0} e^{-c\Phi}$
4. **Reduced mobility within gain layer through trapping** → Gain reduction larger than anticipated from acceptor removal

Defect distribution in the lattice can be modified following three mechanisms:

- ✓ **Diffusion**
- ✓ **Annealing**
- ✓ **Aggregation**

Defect Engineering



Face centered Cubic Si (2-atom base) | Interaction with incoming particle | Interstitial Diffusion | Substitutional Replacement

Acceptor removal, Defect Kinetics (simplified ☺)

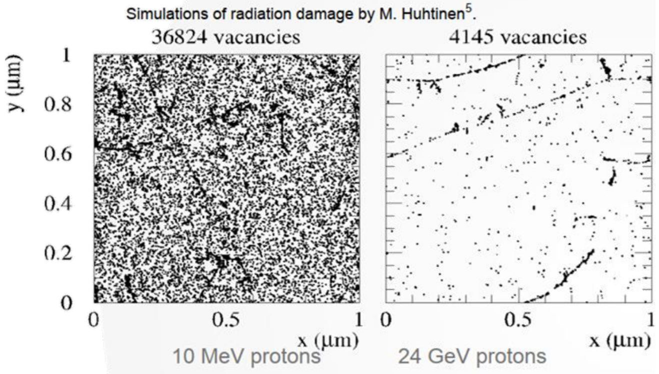
$\mathrm{Rad} + \mathrm{Si_s} \rightarrow \mathrm{Si_i} + \mathrm{B_s} \rightarrow \mathrm{B_i} + \mathrm{O} \rightarrow \mathrm{B_iO_i}$

$\mathrm{Rad} + \mathrm{Si_s} \rightarrow \mathrm{Si_i} + \mathrm{C_s} \rightarrow \mathrm{C_i} + \mathrm{O} \rightarrow \mathrm{C_iO_i}$

Gain layer de-activation too many interstitials, cannot modify

Charge trapping Can be engineered by oxygen trapping

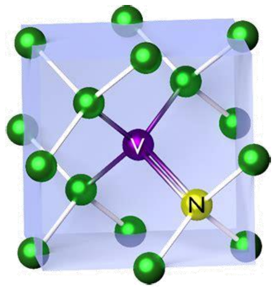
Cluster vs Point Defects



•Introduction

Defects as Tools in Physics

The Nitrogen - Vacancy center in Diamond



$$H = DS_z^2 + \gamma_e \vec{B}\cdot\vec{S} + \vec{S}\cdot\vec{E} + H_{\text{strain}}$$

Zeeman – Magnetic Field

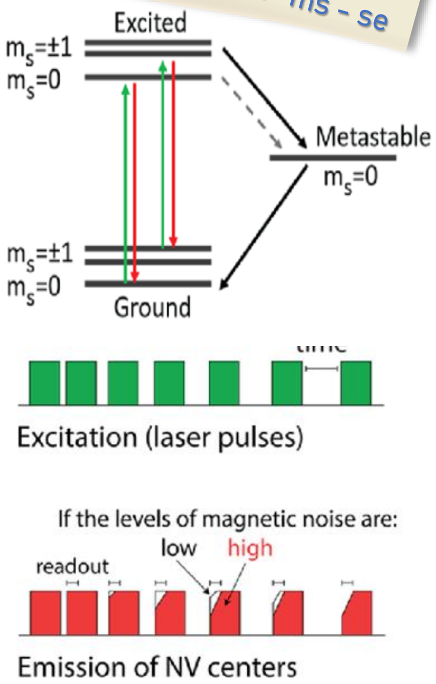
Strain Effect

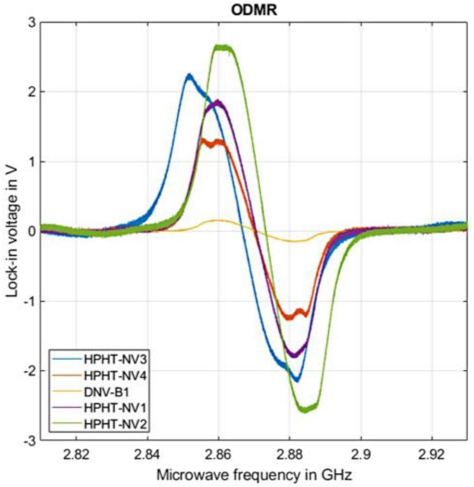
Zero-splitting tern (2.87 GHz ~ 0.12 meV)

Starck – Electric Field

- Nitrogen coupled with vacancy, 1 free e- with spin triplet state (|m_s=0> |m_s=±1 >)
- Energy transition between exited/ground states spin preserving, intermediate transitions non-spin preserving
- Using laser to excite (532 nm) – non spin dependent, one can observe red-light (637 nm) emission intensity
- If external magnetic/electric field or strain alters spin distribution, intensity of emission light modified

Exited state lifetime: 12-20 ns
Spin relaxation time: ~ms - se

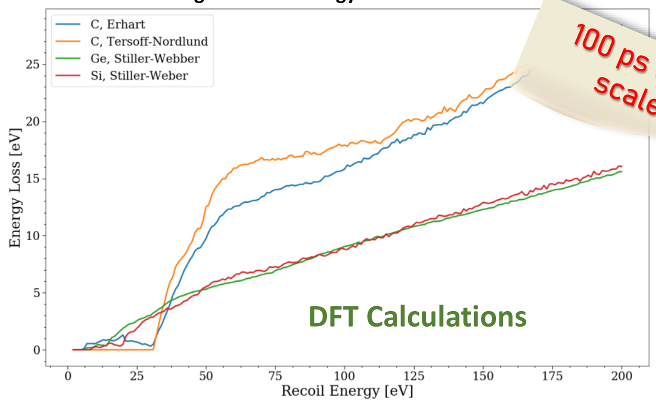




Dark Matter detection via Recoils

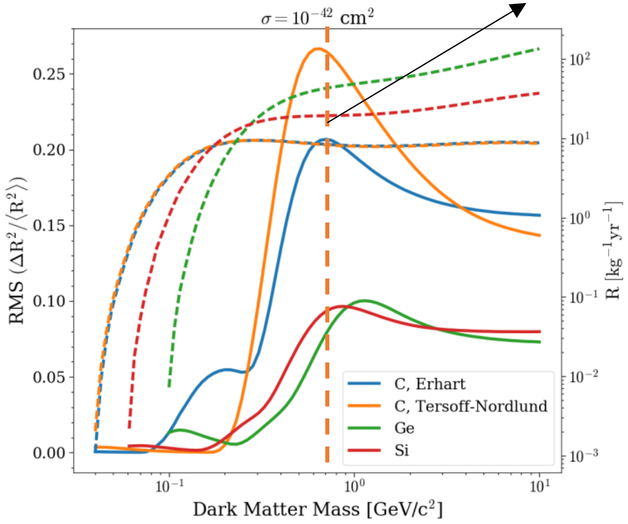
arXiv:2002.03525v2 [physics.ins-det]

- PARCS simulation of 4096 atoms
- 1eV – 200 eV recoils
- Estimate defect generation energy



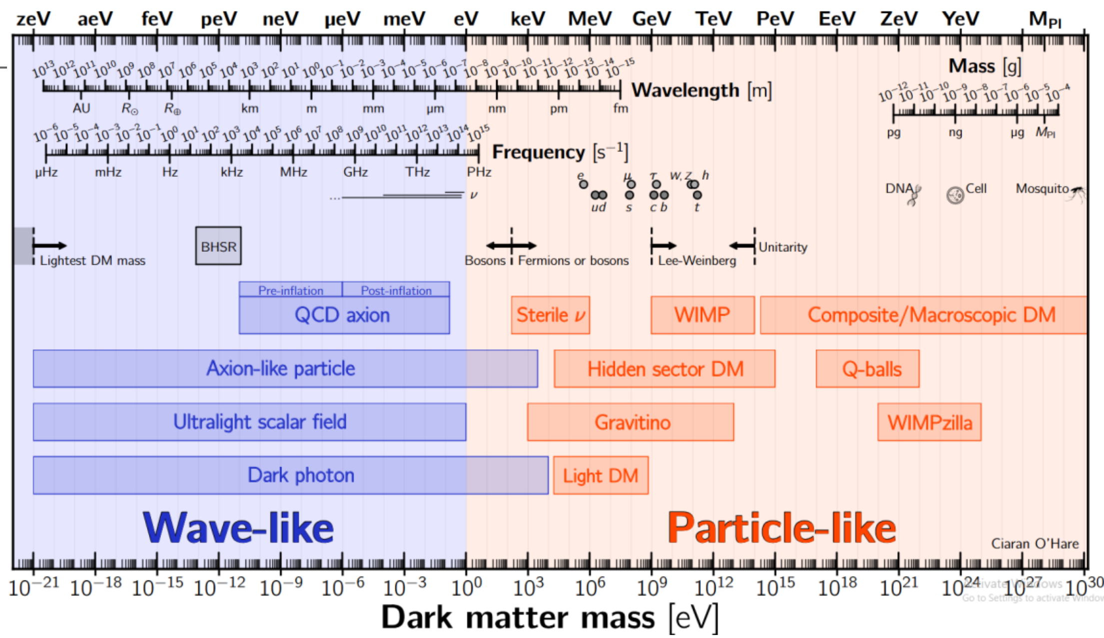
100 ps time scale

For Si, highest sensitivity ~ 0.7 GeV

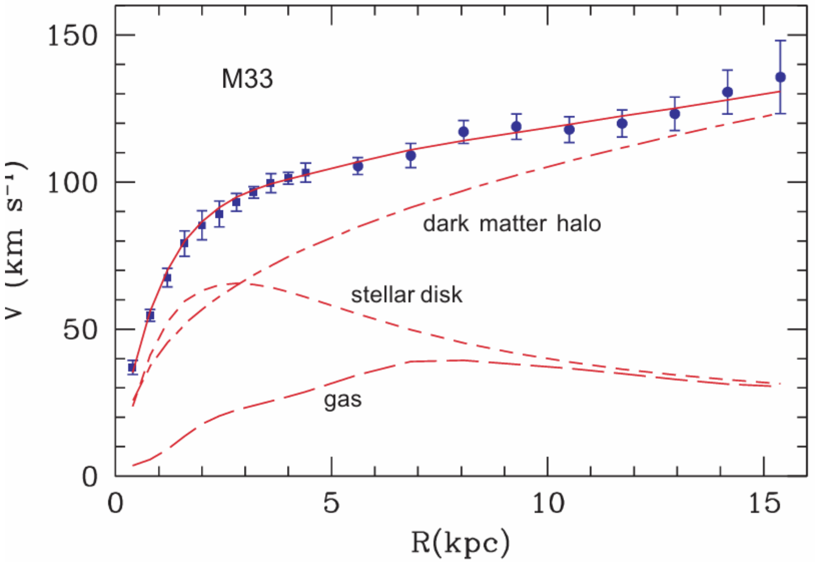


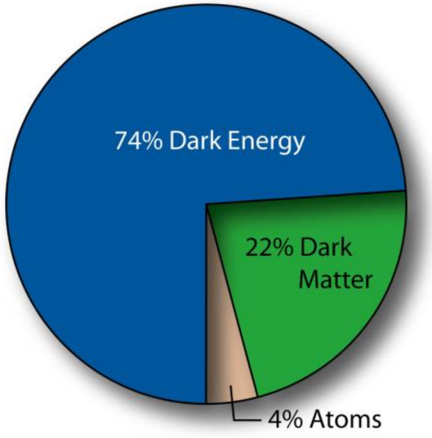
•Dark Matter & Skipper CCDs

What is Dark Matter?



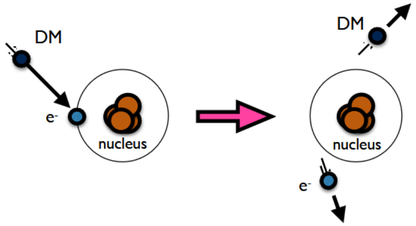
- Dark matter Evidence
  - Galaxy rotation curves
  - Velocity dispersions in binary star bound systems
  - Galaxy cluster studies
  - Gravitational lensing
  - Structures in the CMB angular maps
  - Bullet cluster observations
  - Barrion Acoustic oscillations.
  - ……





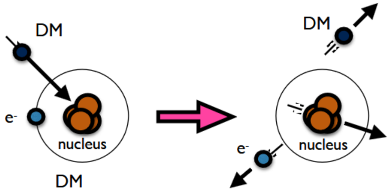
- DM-e scattering

  RE, Mardon, Volansky



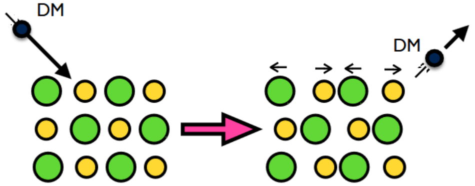
- DM-N scattering via Migdal effect

  Migdal; Vergados & Ejiri; Bernabei; Ibe, Nakano, Shoji, Suzuki



- DM scattering w/ collective modes (e.g. optical phonons)

  Knapen, Lin, Pyle, Zurek



Introduction

Dark Matter Skipper CCDs

Deep Level Transient Spectroscopy

Experimental Setup

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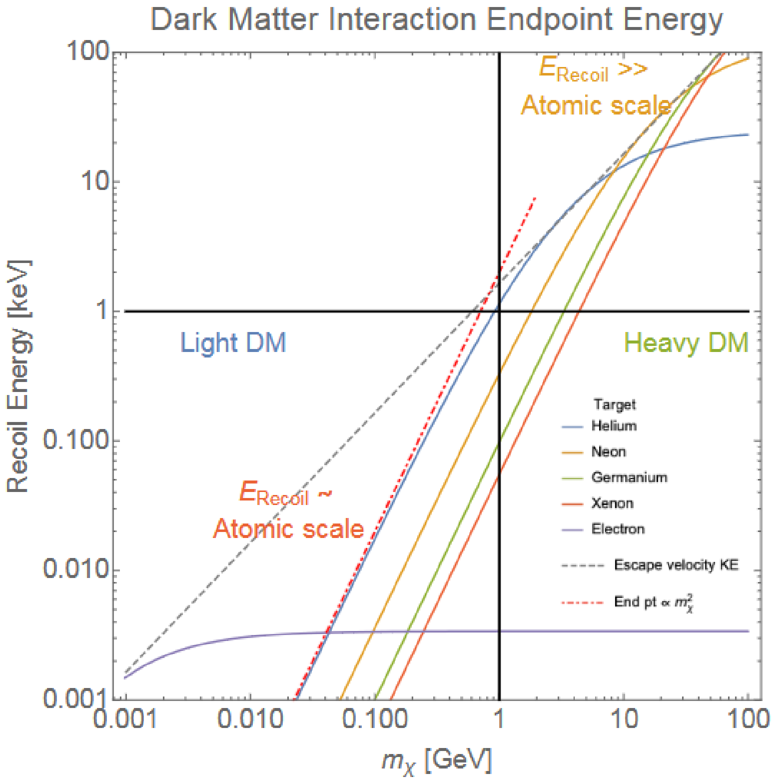
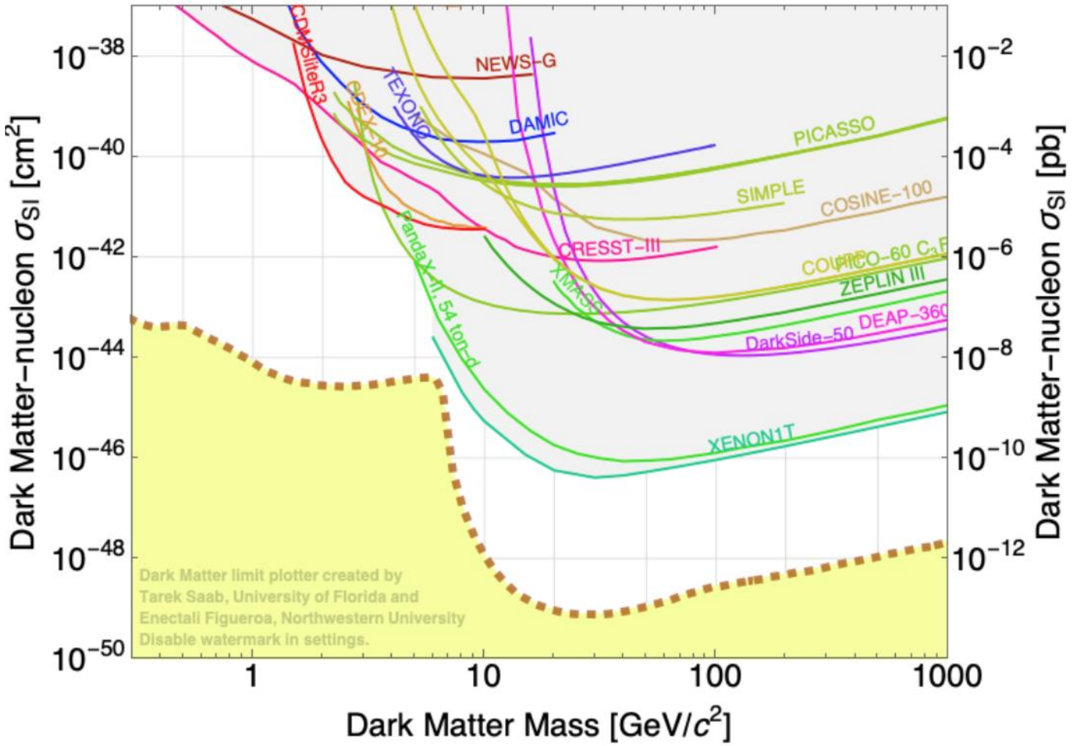
•Dark Matter & Skipper CCDs

Challenges in Direct Detection Experiments

Ancient lead shielding
Electroless cooper (oxygen free)
Strict control of material exposure
Detailed GEANT4 simulations

- Essentially background counting experiments
- Require extremely good modeling of radiogenic / cosmogenic contributions
- Extremely low expected event rate event rate: $\rho_0 = 0.3$ GeV/cm^3 & M = 5 Gev/c^2 → **60 k. particles /cm^3**
- In the 1 – 10 GeV range, once can approximate mainly with nuclear recoil interactions
- Energy transfer thresholds can be a few (~30 keV)

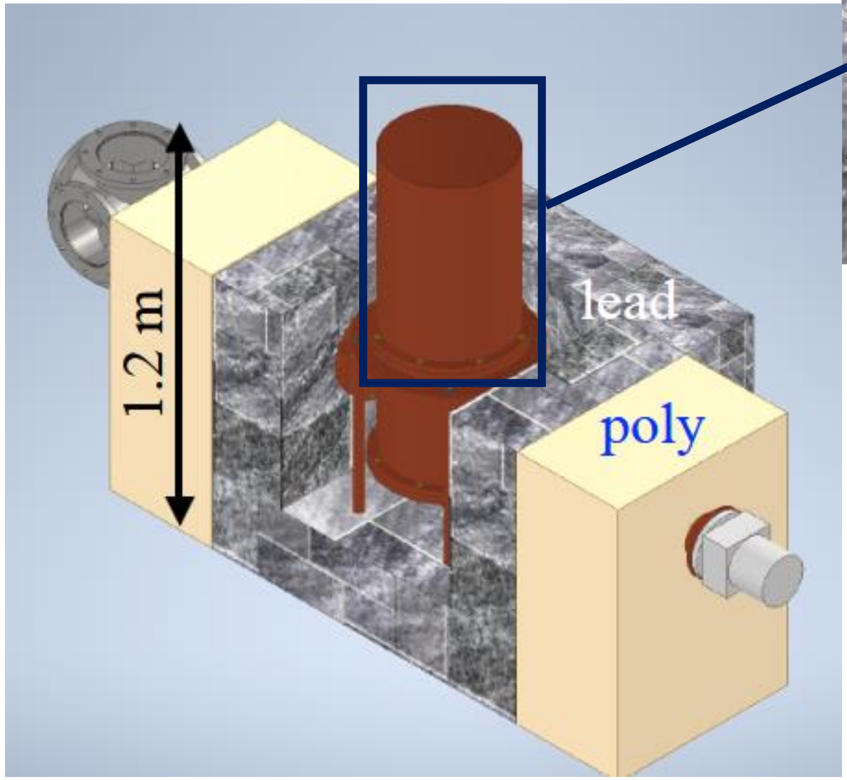




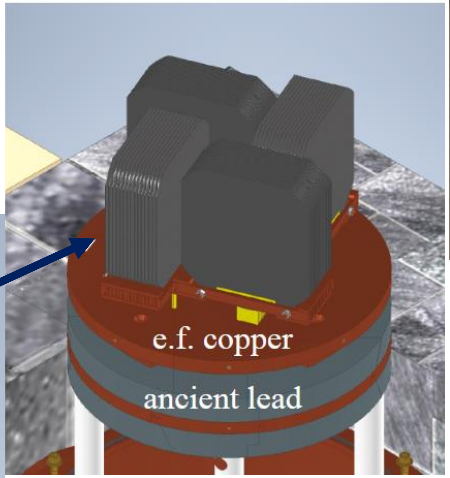
•Dark Matter & Skipper CCDs

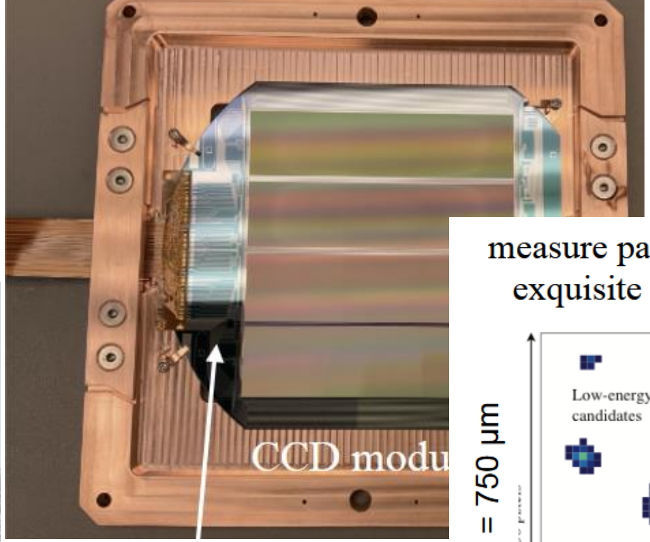
Skipper CCDs as Dark Matter Detectors

- DAMIC-M experiment @ Modane
- 208 CCDs, total mass ~ 0.7 kg
- CCDs @ 130 K, 1 kg yr exposure

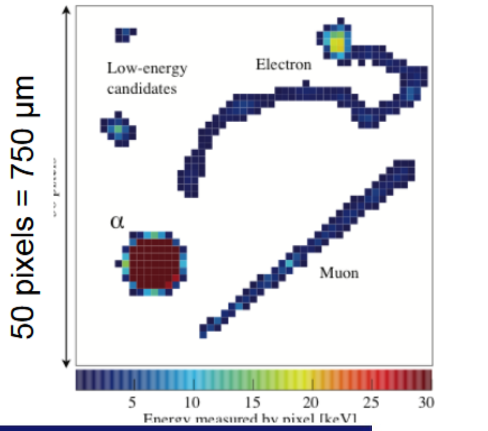


To be installed at LSM, under 1700m of rock





measure particle ionization with exquisite spatial resolution



52 x 4-CCD modules in centrally wrapped Array

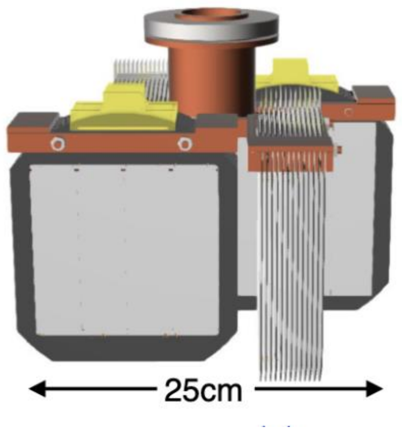
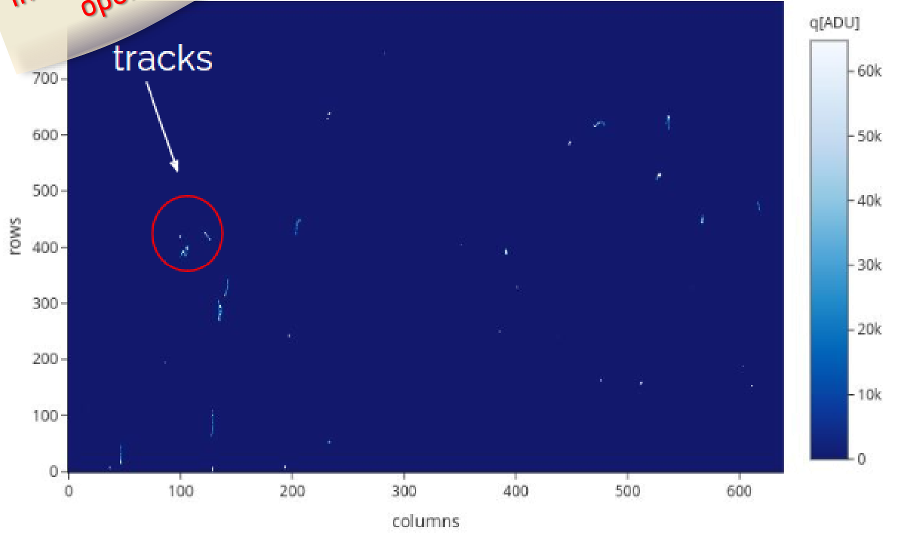


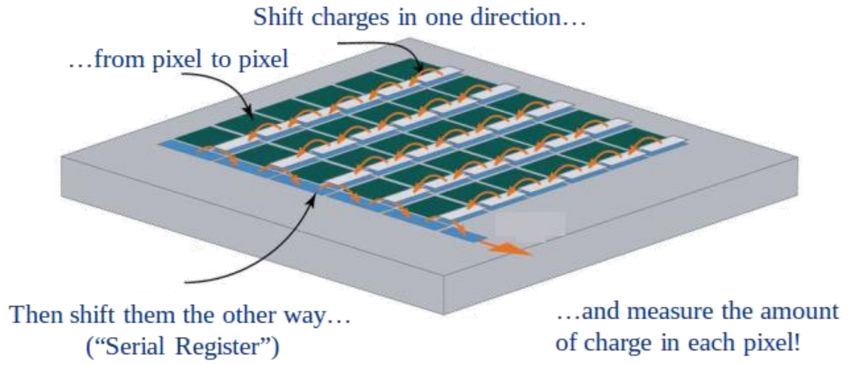
Image from LBC with open shield



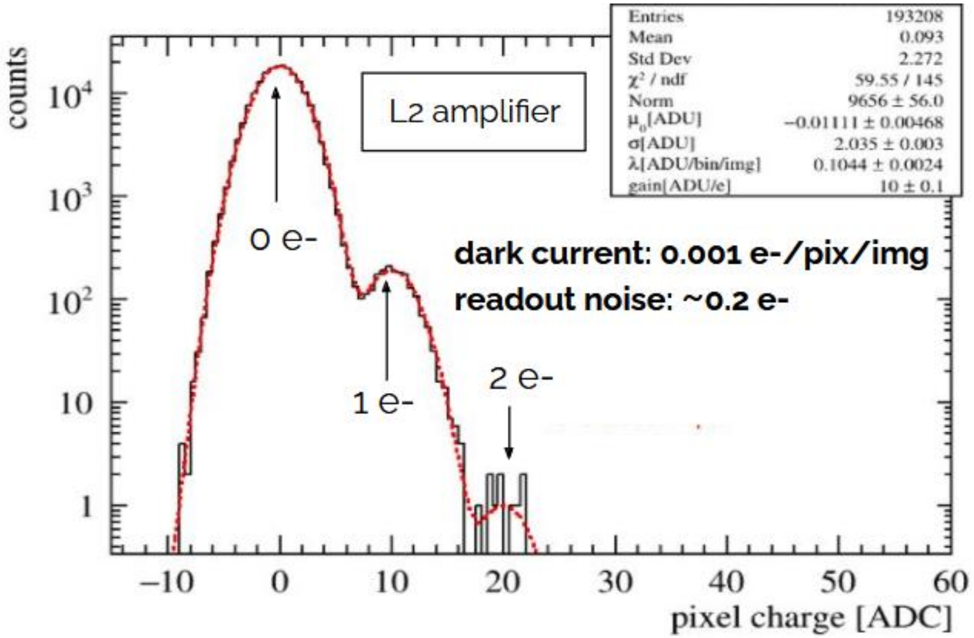
~300 dru

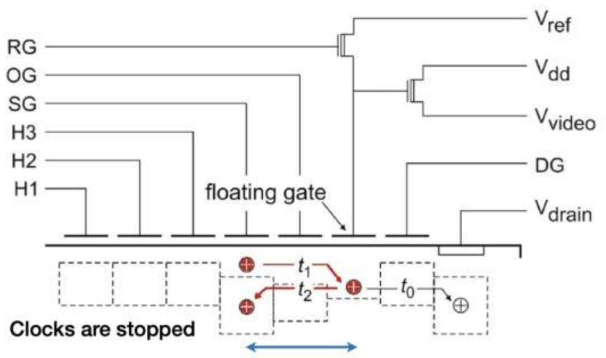
•Deep Level Transient Spectroscopy

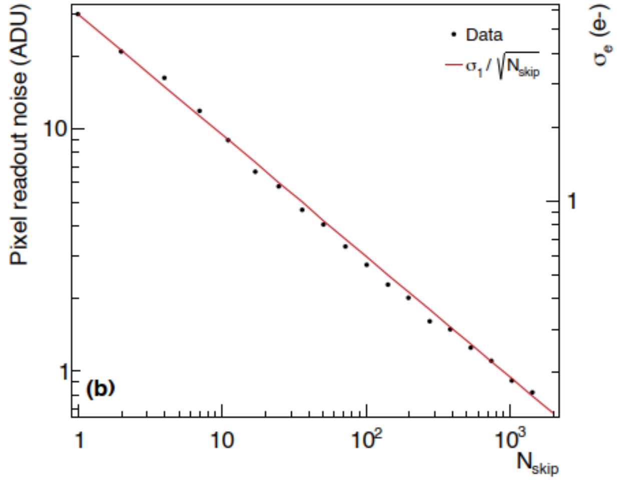
Skipper CCDs as Dark Matter Detectors



- Floating gate design with multiple non-destructive reads of accumulated charge
- $^{1}/_{\sqrt{N}}$ reduction on readout noise
- Lorentz X Gaussian dark current distribution with single electron centered peaks
- 15 μm^2 pixel size with 4 amplifiers in matrix corners, 1k x 6k pixels
- No direct connection to ground for charge evacuation







- Resolution = 0.2e- (< 1eV) at 650 skips
- Dark current = 3.0 × 10^{-3} e-/pixel/day

•Deep Level Transient Spectroscopy

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Dark Matter Skipper CCDs

Deep Level Transient Spectroscopy

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Principles and Methodology

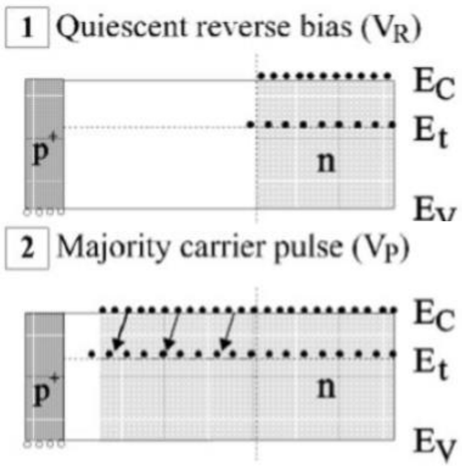
Measurement cycle at fixed T

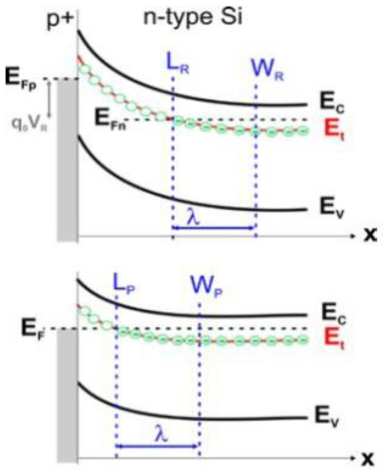
[1] reverse bias V_R

- junction under reverse bias
- defect states are not occupied

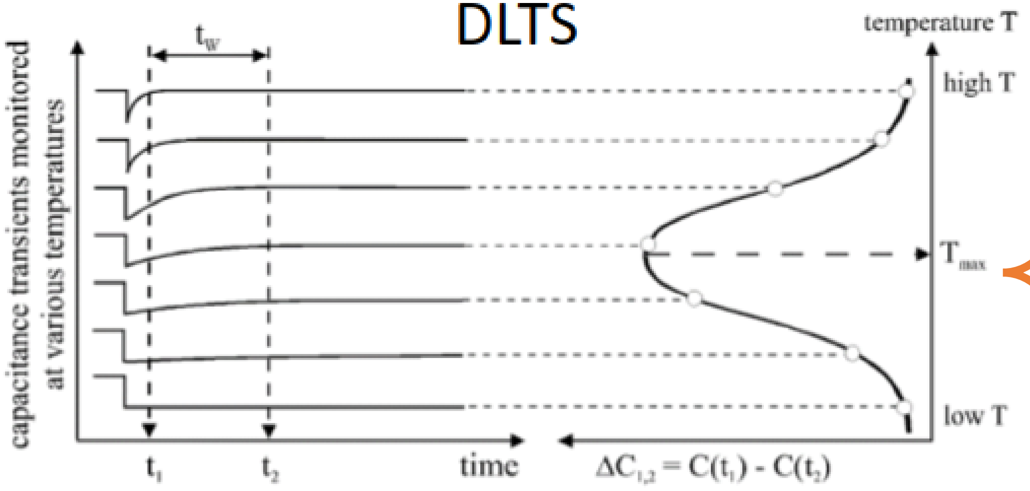
[2] injection pulse V_P

- reduction of reverse bias
- injection of majority carriers
- occupation of defect levels

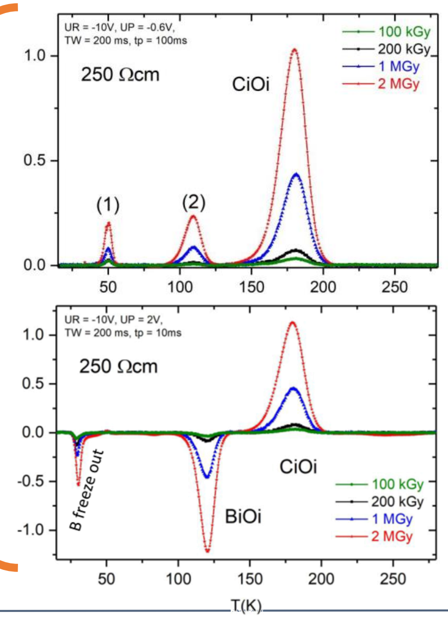


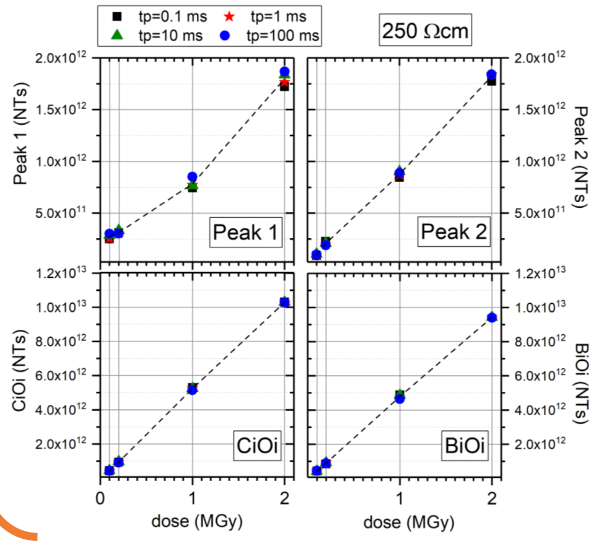


DLTS



Temperature scan while injecting





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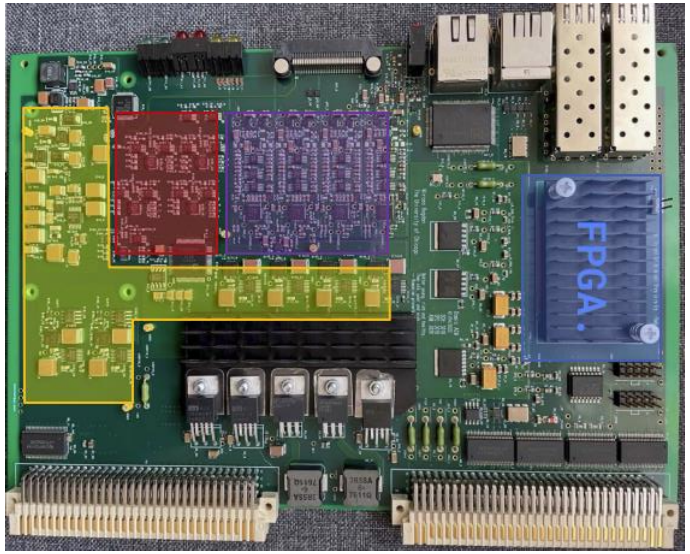
•Deep Level Transient Spectroscopy

Implementation on Skipper CCDs

- Every CCD readout system needs four components:
  - Bais circuits: on-chip preamplifier biasing
  - Clock generation: timing and charge shift for readout
  - Singal digitization: ADC channels for sampling
  - Control / connect logic: FPGA / microcontroller



DAMIC-M Acquisition / Control Module (ACM)

Issues with DLTS in CCDs

- No timing information available → **Get timing information at the source by varying injection pulse length**
- Transients inaccessible → **Use phase displacement and scan over all available values to compensate**
- Pixelized structure → **Use Fourier deconvolution with pixel information deducted by clock cycle**

- Perform regular DLTS matrix scans in fixed intervals and corelate with recorded clusters to identify new / annealed defect for noise control
- Perform comparative matrix assessment as a handle to increase dark mater sensitivity

•Deep Level Transient Spectroscopy

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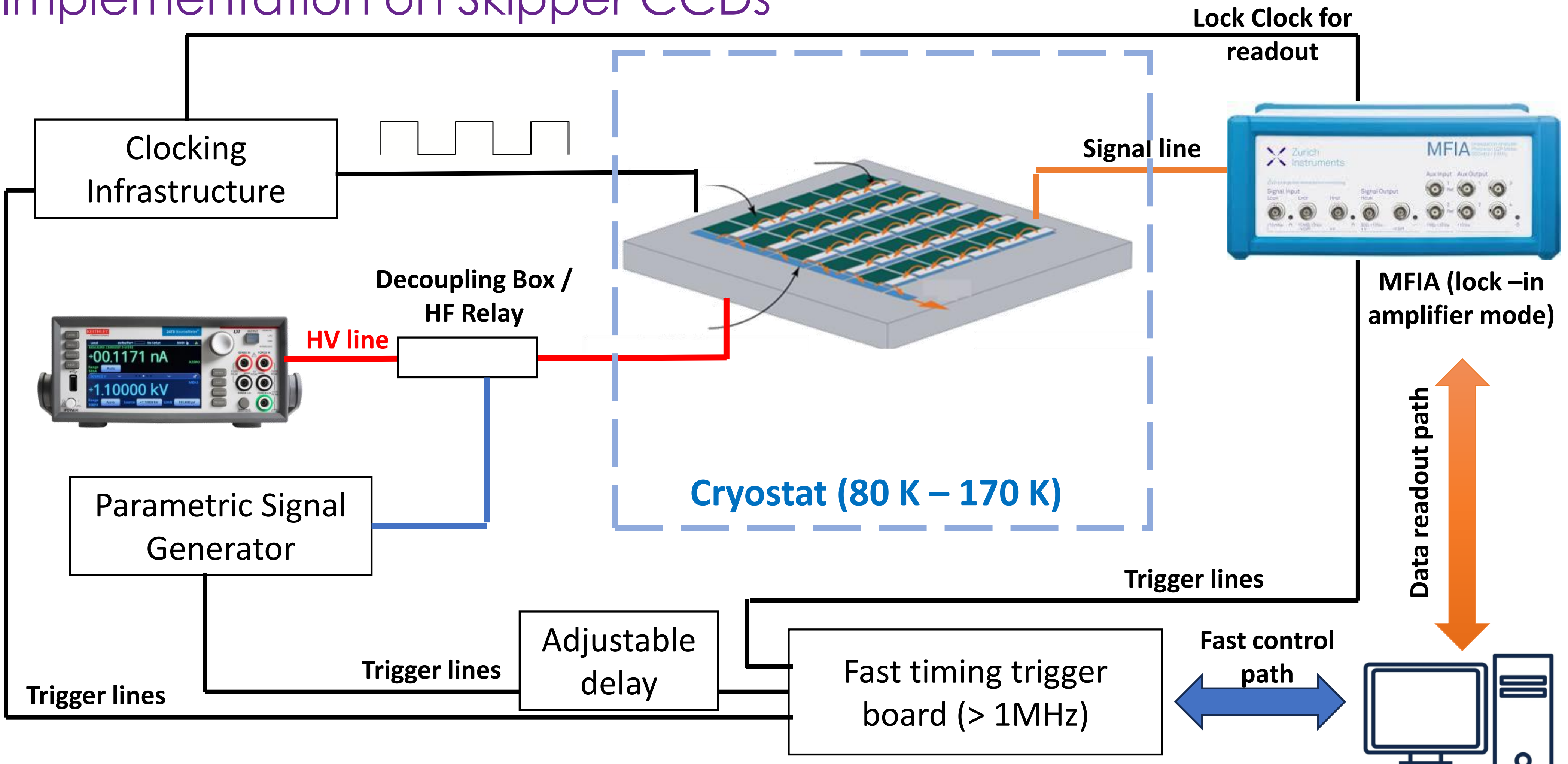
Implementation on Skipper CCDs



One measures capture cryosections by leveraging injection and readout clock with fast triggering

•Experimental Setup &Results

Overview and Current Status

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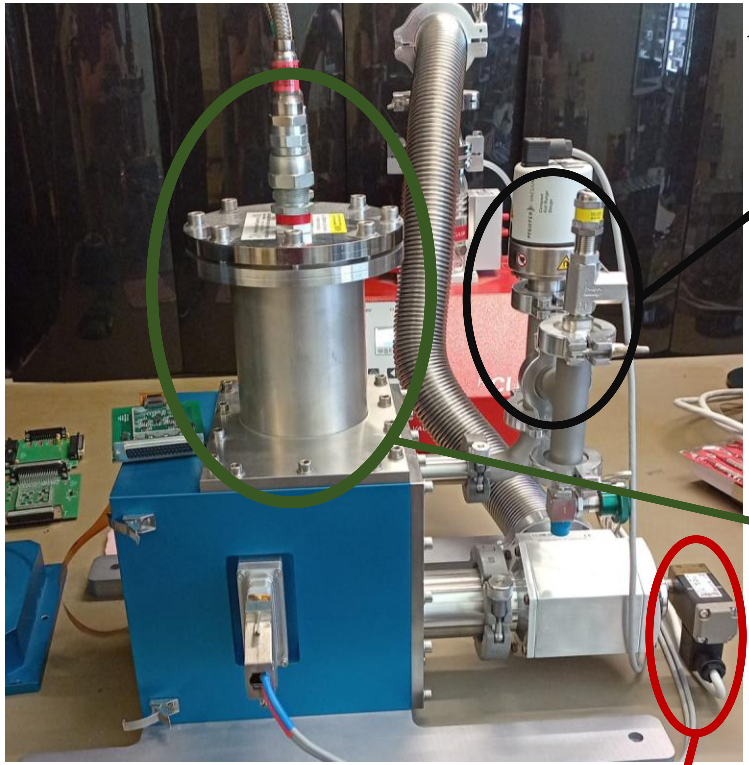
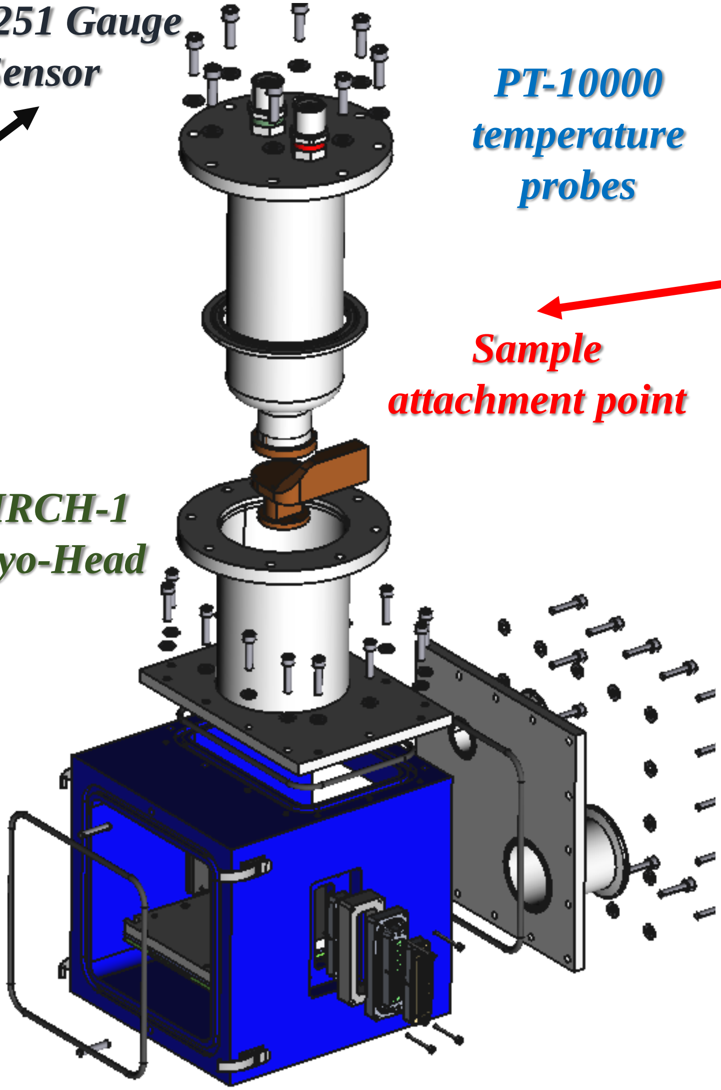
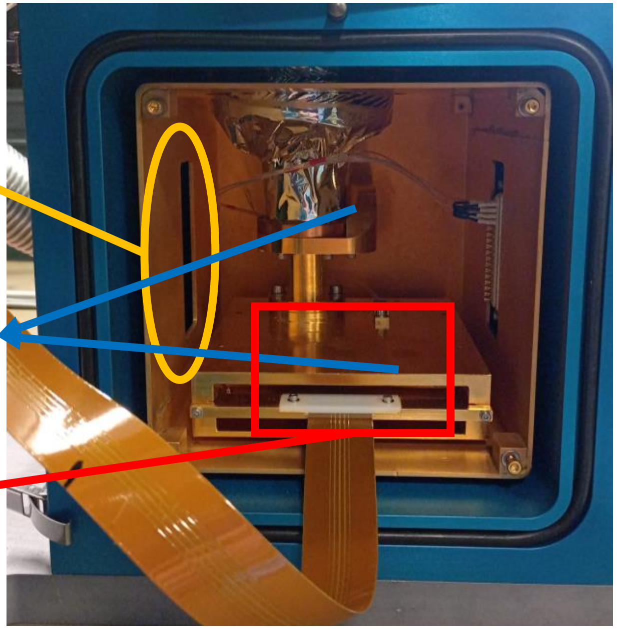






PKR 251 Gauge Sensor

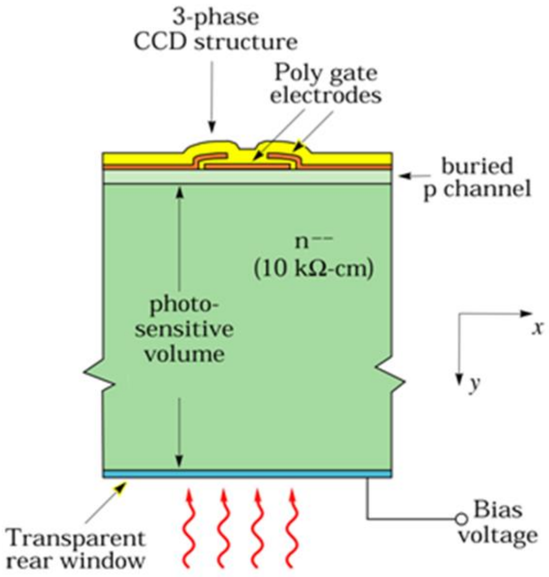
MRCH-1 Cryo-Head

Bürkert W29MA Solenoid Valve

DB50 Pass-through Opening

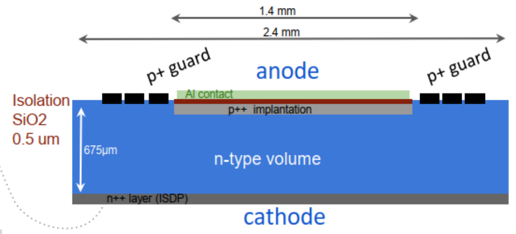
PT-10000 temperature probes

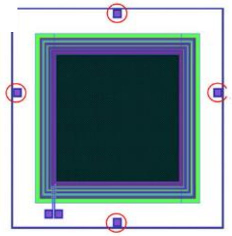
Sample attachment point

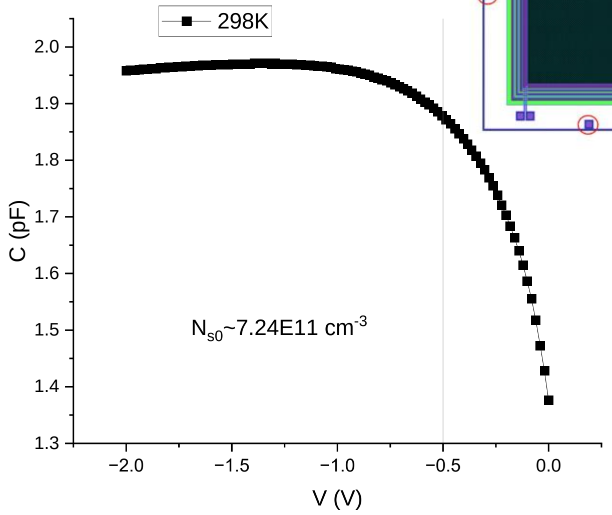


•Experimental Setup &Results

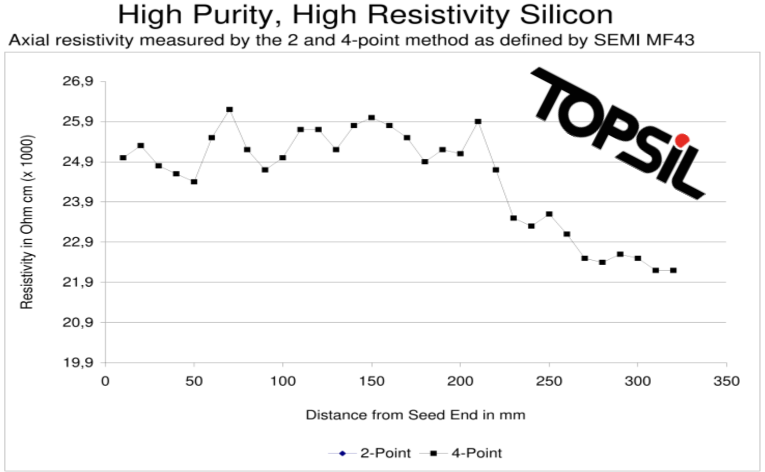
Structures and substrate

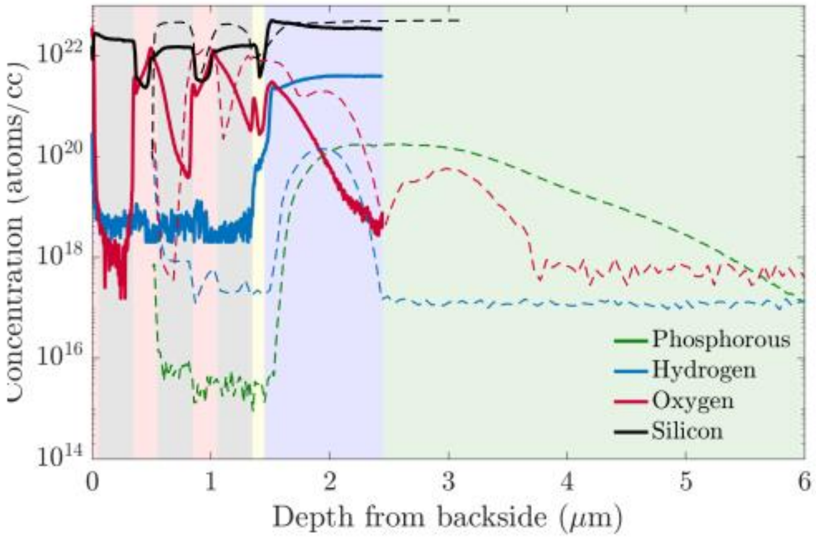




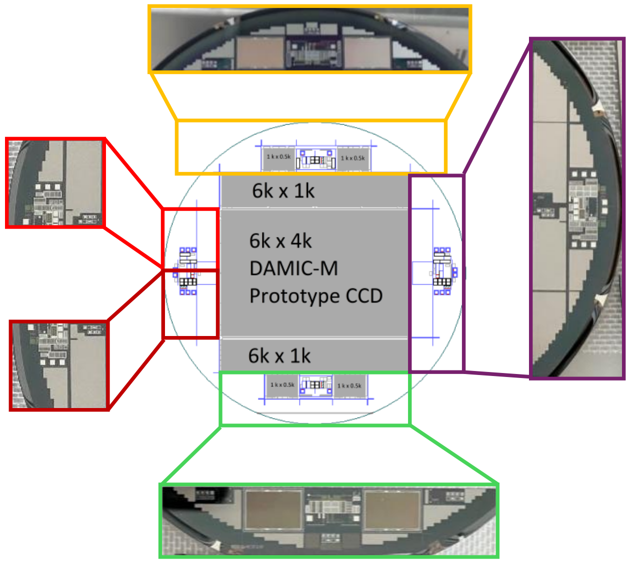


- n-type Float zone square diodes
- 675 µm high resistivity substrate
- 22 kOhm×cm high purity silicon
- 1.4 x 1.4 mm active surface
- Capacitance of 3.4 pF





DAMIC-M Wafer



Small CCD (1022 x 682)

Pixel Area length:9.9 mm
Total length: 12.3 mm
Width: 16.92 mm

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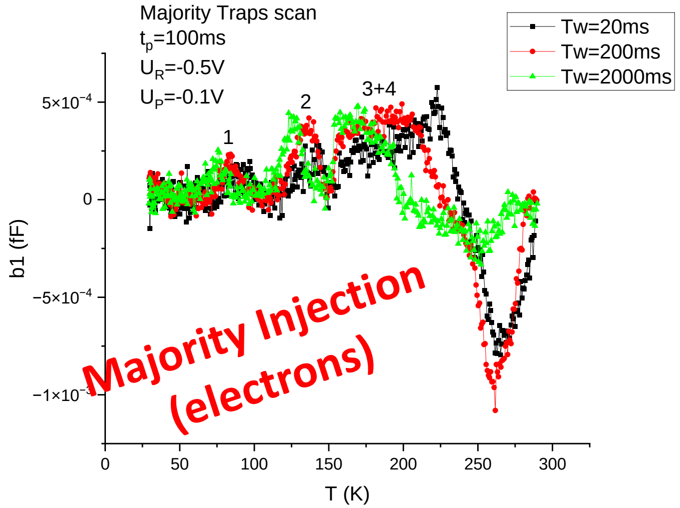
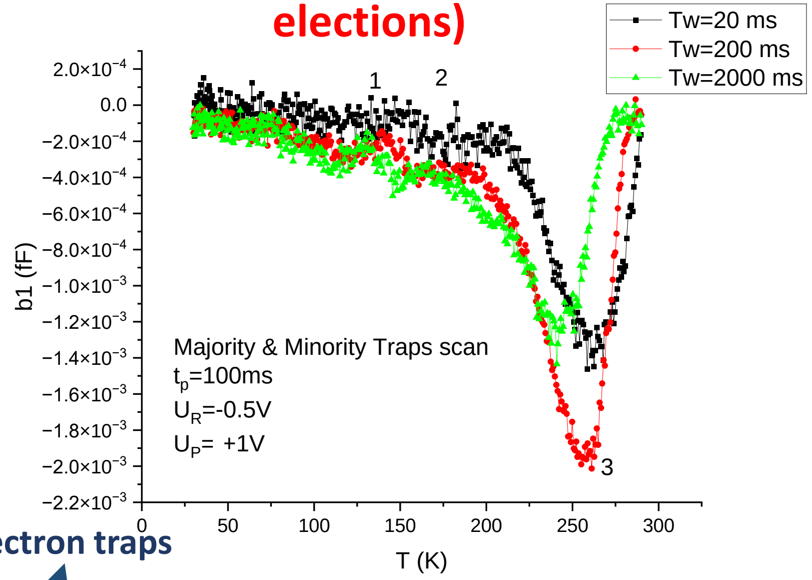
•Experimental Setup &Results

Initial results on test structures – **NON IRRAD**

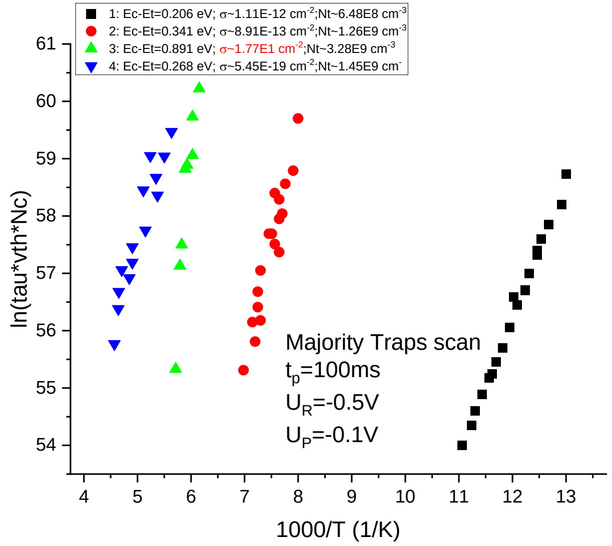


- Measurement at 1 MHz!
- Estimated carrier concentration: $N_{s0} \sim 7.24 * 10^{11} cm^{-3}$
- N type sample
- Area=$1.96 * 10^{-2}\ cm^2$
- 100 ms integration window
- - 0.5 V / +1 V injection pulses
- -0.5 V Bias Voltage

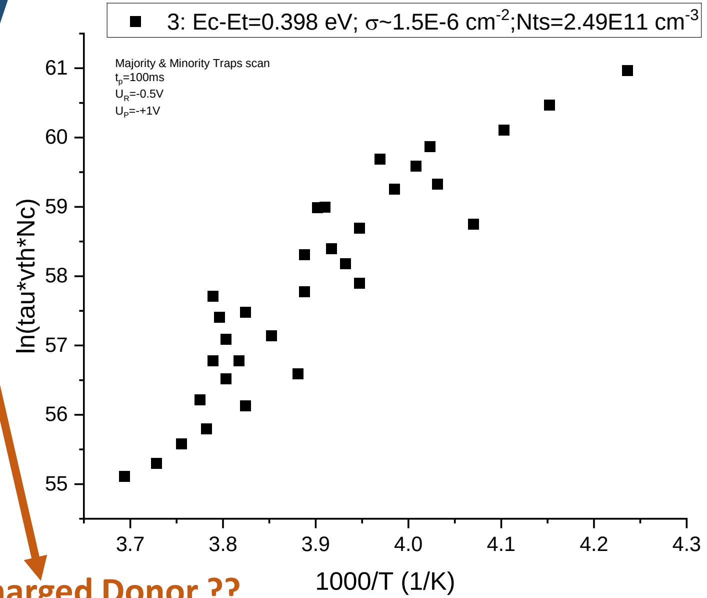
Minority & Minority Injection (holes + elections)



Electron traps



	Energy Level (eV)	Concentration N/cm³	Capture Cross-section (cm⁻²)
Majority	0.206	6.48 ×10⁸	1.109 ×10⁻¹²
	0.341	1.262 ×10⁸	8.912 ×10⁻¹³
	0.891	3.284 ×10⁸	1.773 ×10¹
	0.268	1.446 ×10⁹	5.451 ×10⁻¹⁹
Minority & Minority	0.239	8.165 ×10⁸	2.11 ×10⁻¹⁵
	0.296	9.871 ×10⁸	1.361 ×10⁻¹⁶
	0.947	2.45 ×10¹¹	3.274 ×10⁻⁷



Repulsive center - Charged Donor ?? (upper bandgap part)

•Conclusions

Introduction

Dark Matter Skipper CCDs

Deep Level Transient Spectroscopy

Experimental Setup

Conclusion

- First presentation of concrete defect-based method for dark matter detection
- Expected increase in sensitivity and better noise mitigation
- Target implementation at CCD based Dark Matter experiments (DAMIC-M, DAMIC@SNOLAB, OSCURA) with **minimal** hardware intervention
- Phase displacement and Fourier deconvolution for pixel-level analysis

- **Current Status**
  - Initial measurements prove sufficient sensitivity
  - Test structures available at high numbers
  - Setup implemented with necessary hardware

- **Next Steps**
  - First injection on CCDs though HV line for electronic state pumping
  - Implementation of clock-synchronized lock-in amplifier
  - 2D mapping of defects of several matrices to verofy consistency


BACKUP SLIDES
DO NOT OPEN UNLESS TOLD SO

•Deep Level Transient Spectroscopy

Principle

Measurement cycle at fixed T

[1] reverse bias V_R

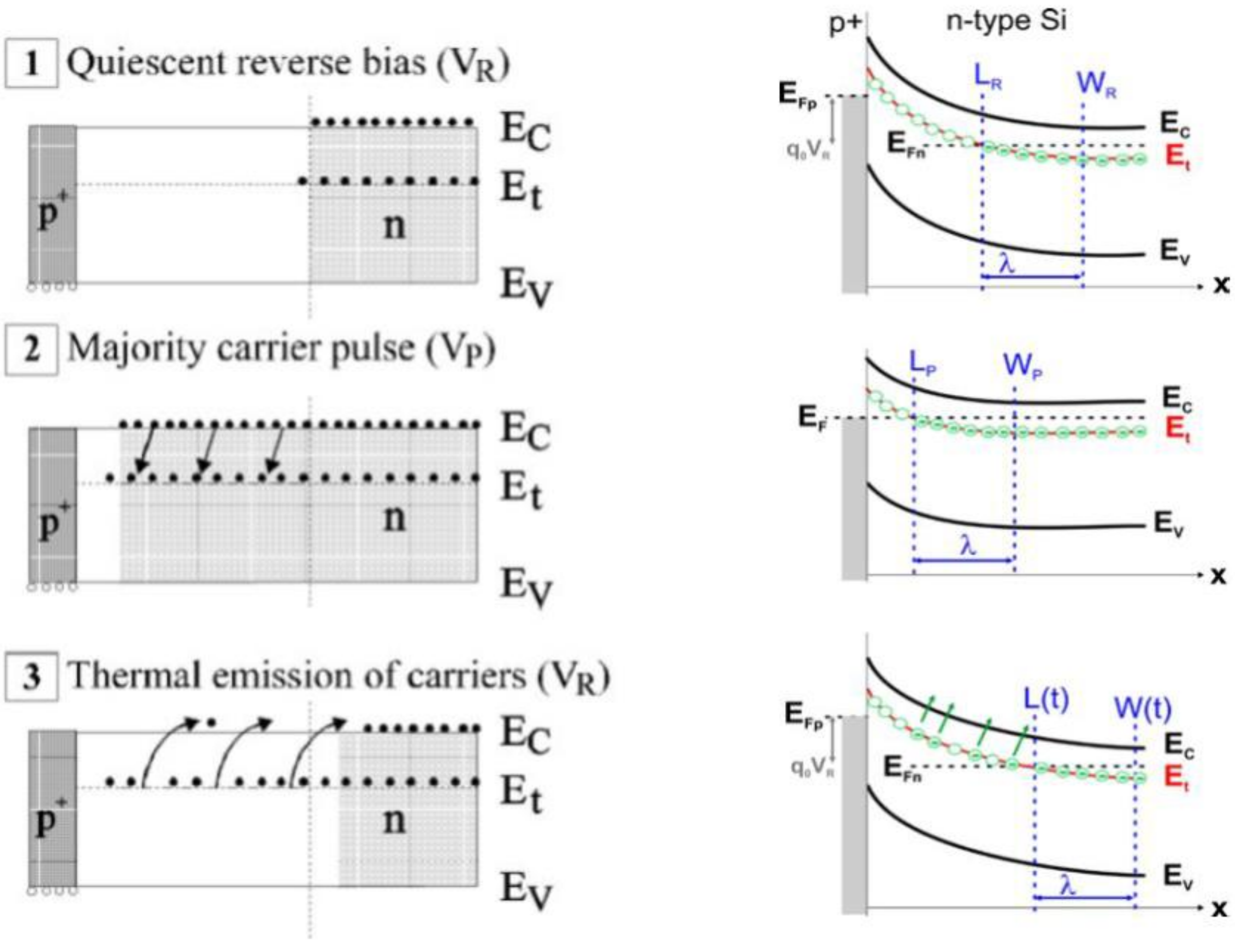
- junction under reverse bias
- defect states are not occupied

[2] injection pulse V_P

- reduction of reverse bias
- injection of majority carriers
- occupation of defect levels

[3] reverse bias V_R

- junction under reverse bias
- thermal emission of carriers
  - expansion of depletion zone
  - decrease of capacitance



•DAMIC-M System – Electronics Rack

Instrumentation

- Compact transportable system
- Lan only control/data connections
- Fully protected internal network (NAT/router)

Vacuum - Temperature

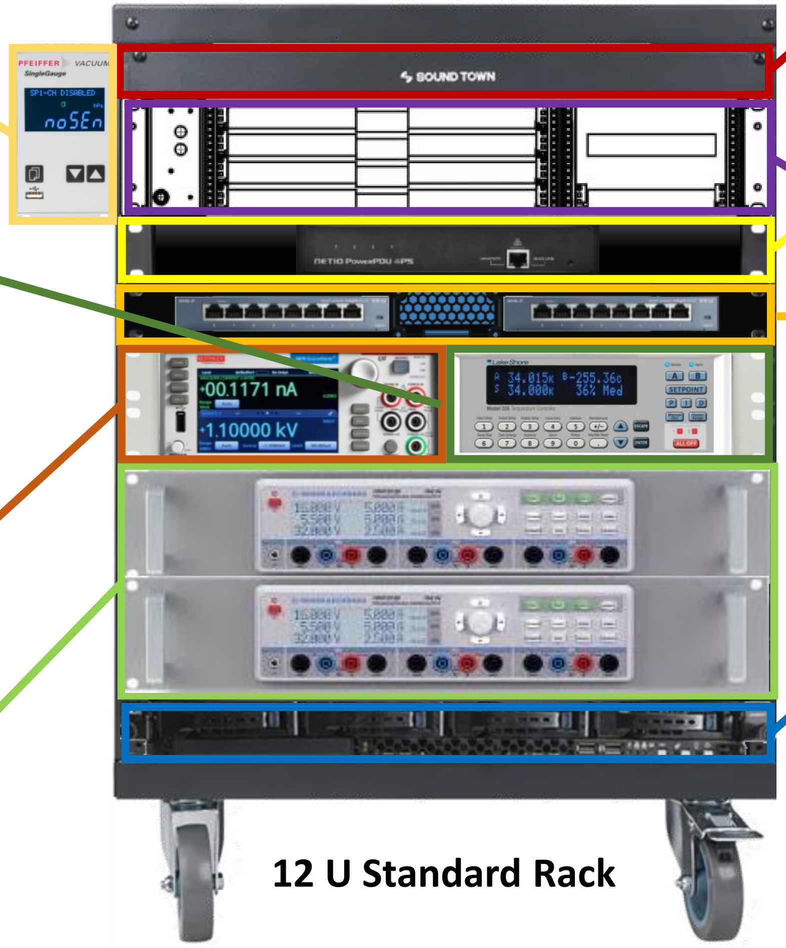
Pfeiffer Vacuum TPG 361, Single Gauge + PKR 251 Gauge Sensor

Lakeshore 335
cryogenic temperature controller

Low and High Voltage

Keithley 2470 High Voltage Source Meter, 10 fA resolution, 2 µV Noise RMS

R&S HMP2030 3-channel low voltage power supply (5 A, 32 V, 80 W per channel)



12 U Standard Rack

Power Management

Safety rack-mounted (19”) power distribution block

NETIO PowerPDU 4PS
(4 input LAN programmable mains)

DAQ System / Control

CAEN VME8004X
2U 4 Slot VME64X Mini Crate

1×

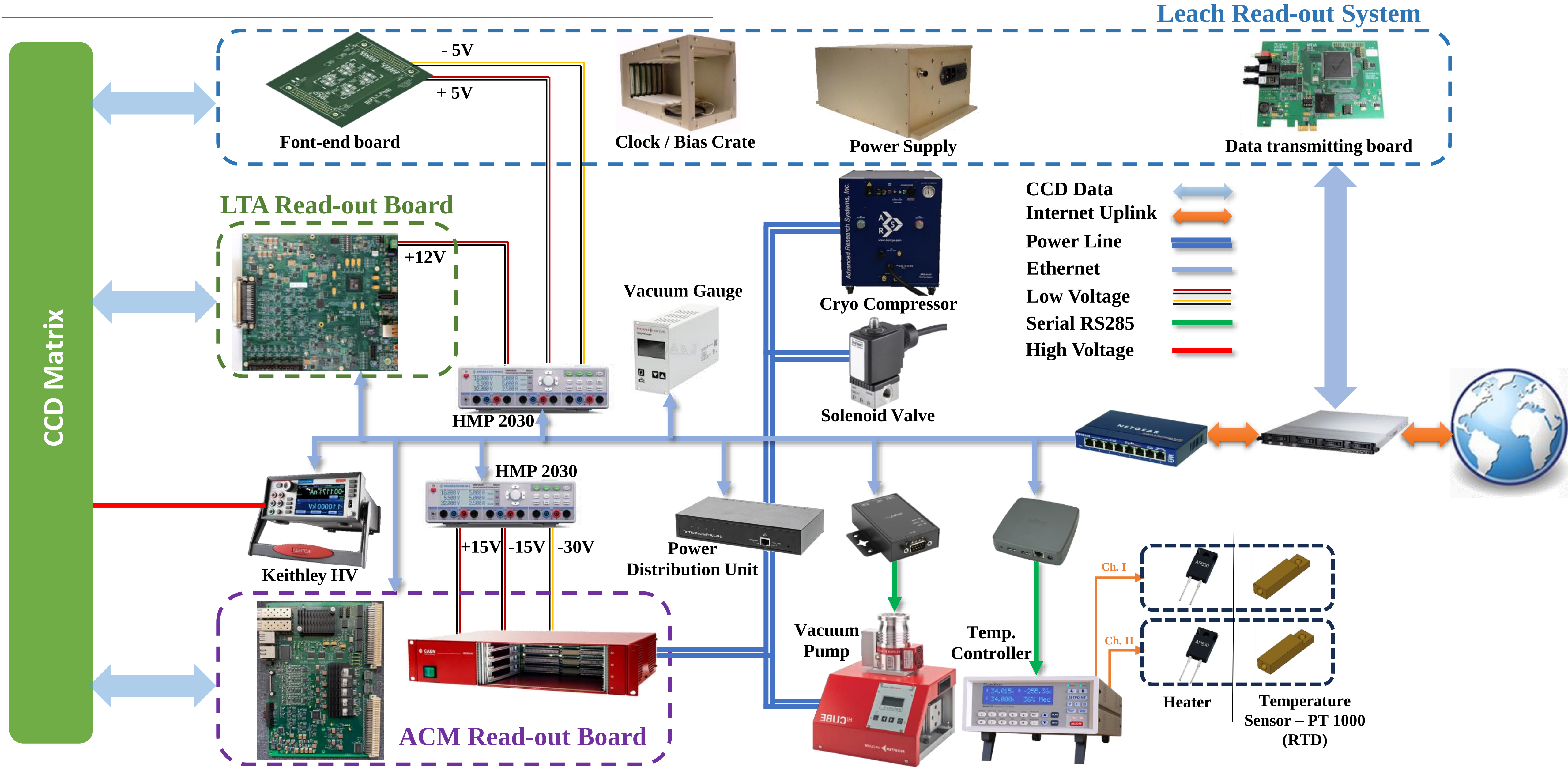
Asus RS300-E7/PS4
1U Server with Quad LAN
4 x 4TB HotSwap Drives on RAID 10

Network Management

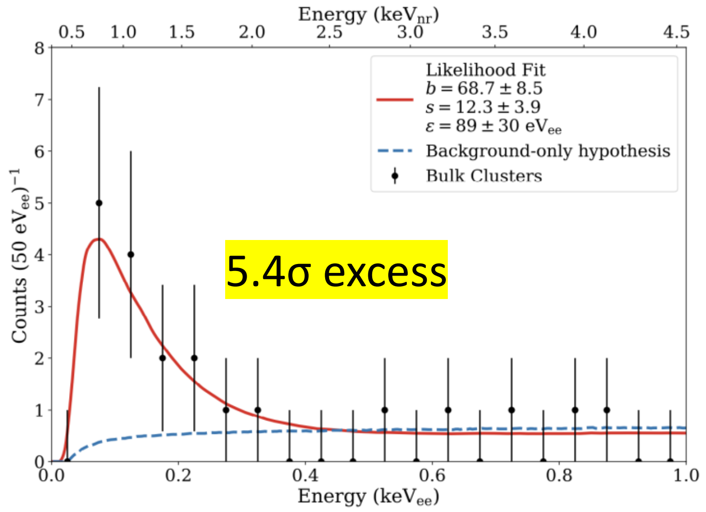
2×

NETGEAR ProSAFE GS108
8 port Gigabit Switch

•Slow Control and Data bus



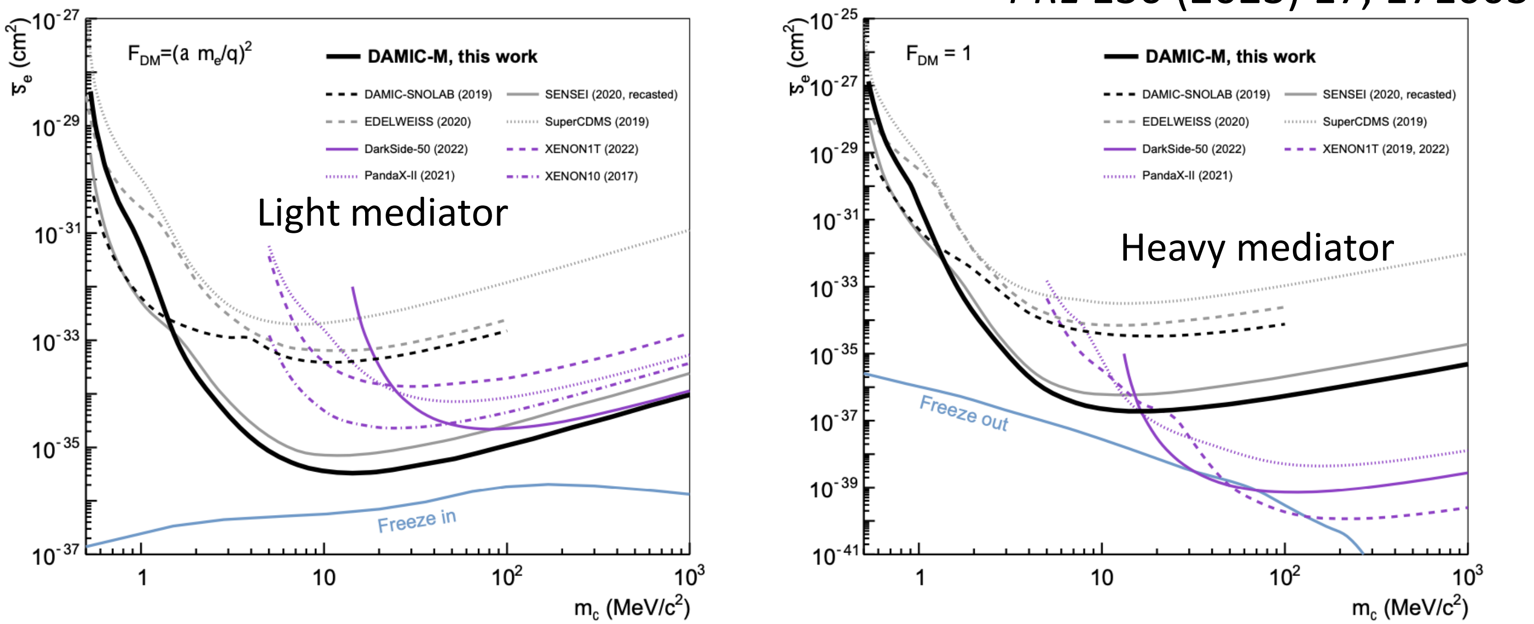
•DAMIC Experiment



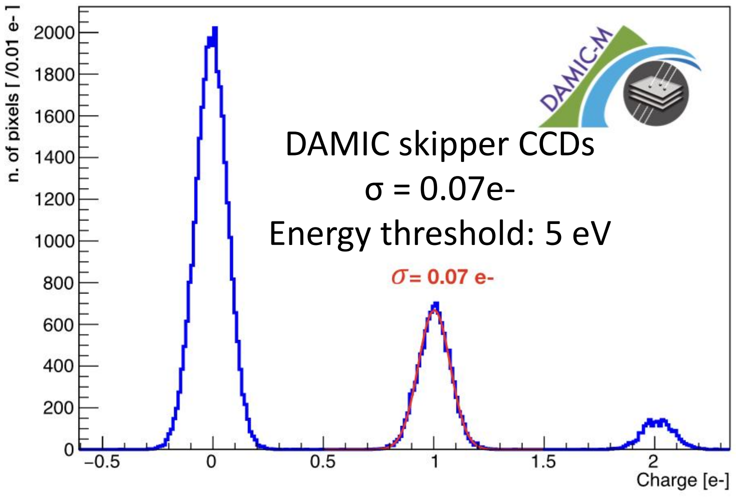
2023: DAMIC@SNOLAB observes low-mass 5.4 Sigma excess using skipper CCDs confirms previous 3.4 σ excess (PRL. 125 (2020) 241803)

Sub-GeV DM searches

PRL 130 (2023) 17, 171003

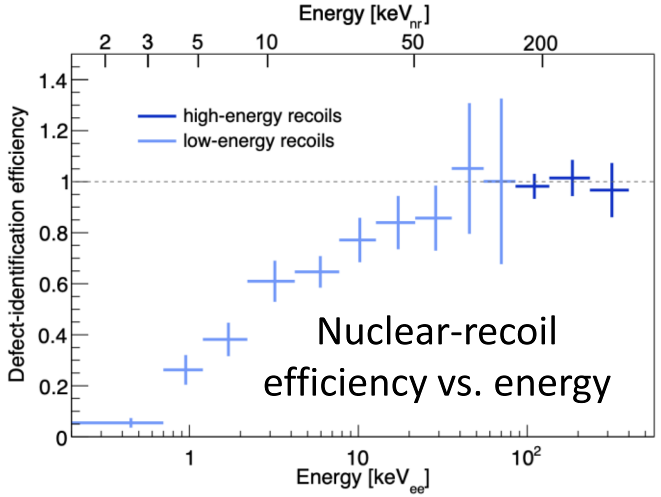


DAMIC-M 2023 world-leading searches for DM-electron scattering

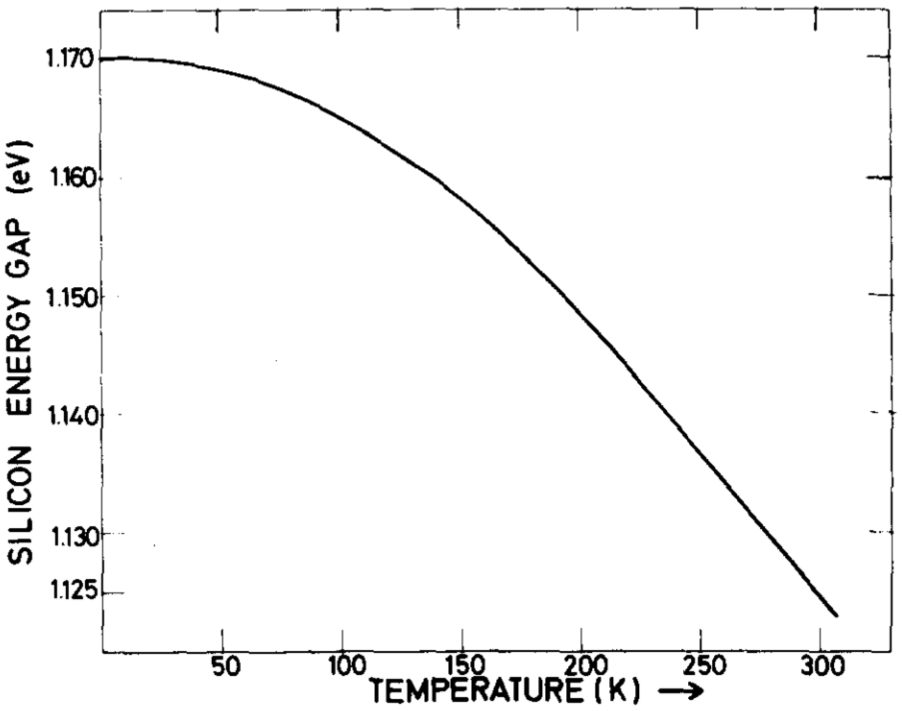


UZH group pioneering new technique of using silicon lattice defects (radiation damage) to identify DM nuclear recoils

Gives CCDs capability to distinguish nuclear and electronic recoils !



•Silicon Leakage Current Temperature dependence



- Measurement performed using optical excitation and studying absorption coefficient resonances
- Sample of p-type, FZ, 10^{12} cm^3 dopant concentration

At 0 K theoretical maximum of 1.1701 eV, drops to 1.1249 ev at 300 K

Origin: Relative position shift of conduction-valence bands

- ✓ **Temperature dependent electron-lattice interaction**
  - ➢ Equivalent to the "Brownian effect", but in a band structure
  - ➢ Accounts for the major contribution to the change
  - ➢ Temperature dependence:

$\Delta E_{gi} \sim T^2$ for T<<Θ & $\Delta E_{gi} \sim T$ for T>>Θ

θ for Si: 645 K (Debye Température)

- ✓ **Thermal-related lattice dilatation**
  - ➢ Linear at high temperatures
  - ➢ Only accounts for 25 % of the total bandgap variation
  - ➢ Non-linear at low temperatures

Bụl̃l Ěğğêçţĵş

Sources of dark current in semiconductors:

- ✓ Generation current (I_g)
- ✓ Trap Assisted tunneling (TAP), Fowler - Nordheim formula
- ✓ Field Assisted tunneling (Pool-Frenkel emission)
- ✓ Impact ionization (E > 15 V / μm)

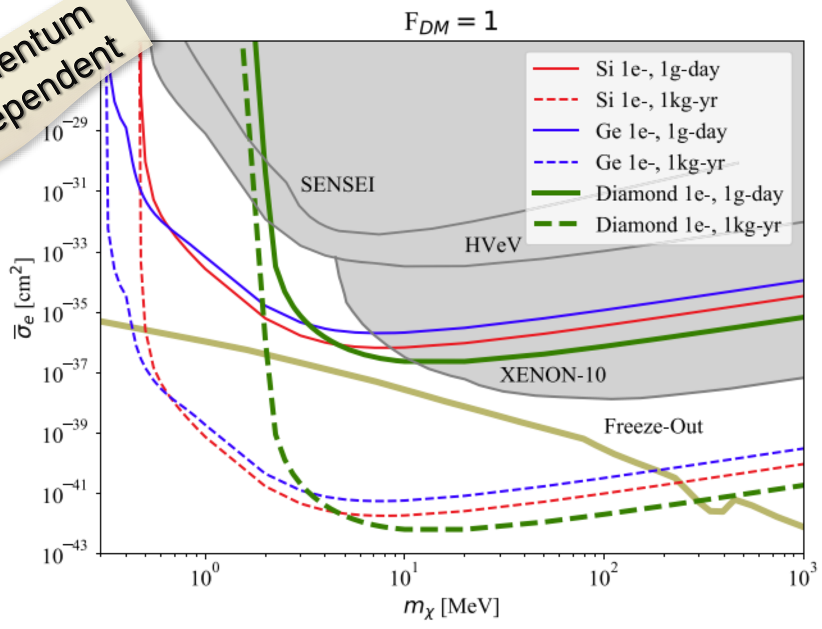
Effects reducing dark current:

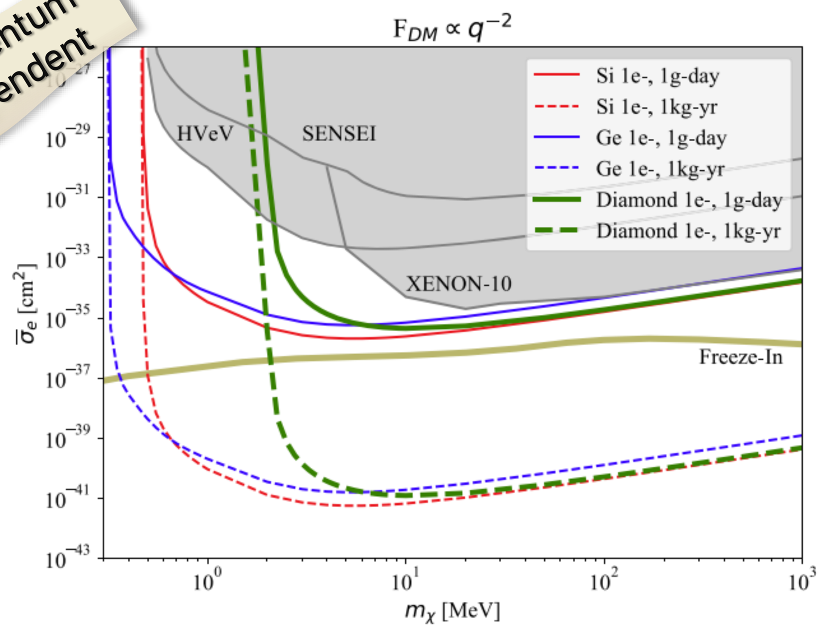
- ✓ Recombination

Momentum independent

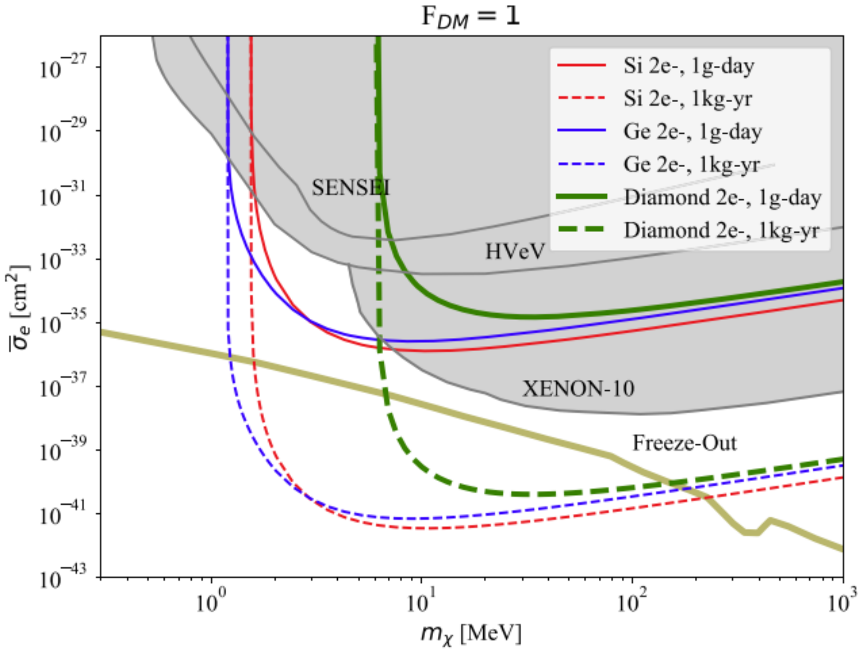
Momentum dependent

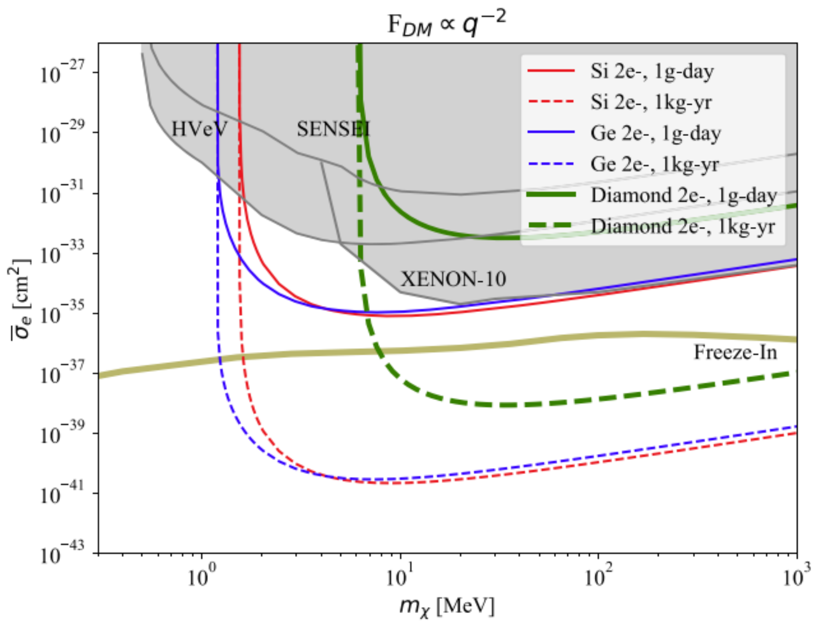
1 e-h pair limit

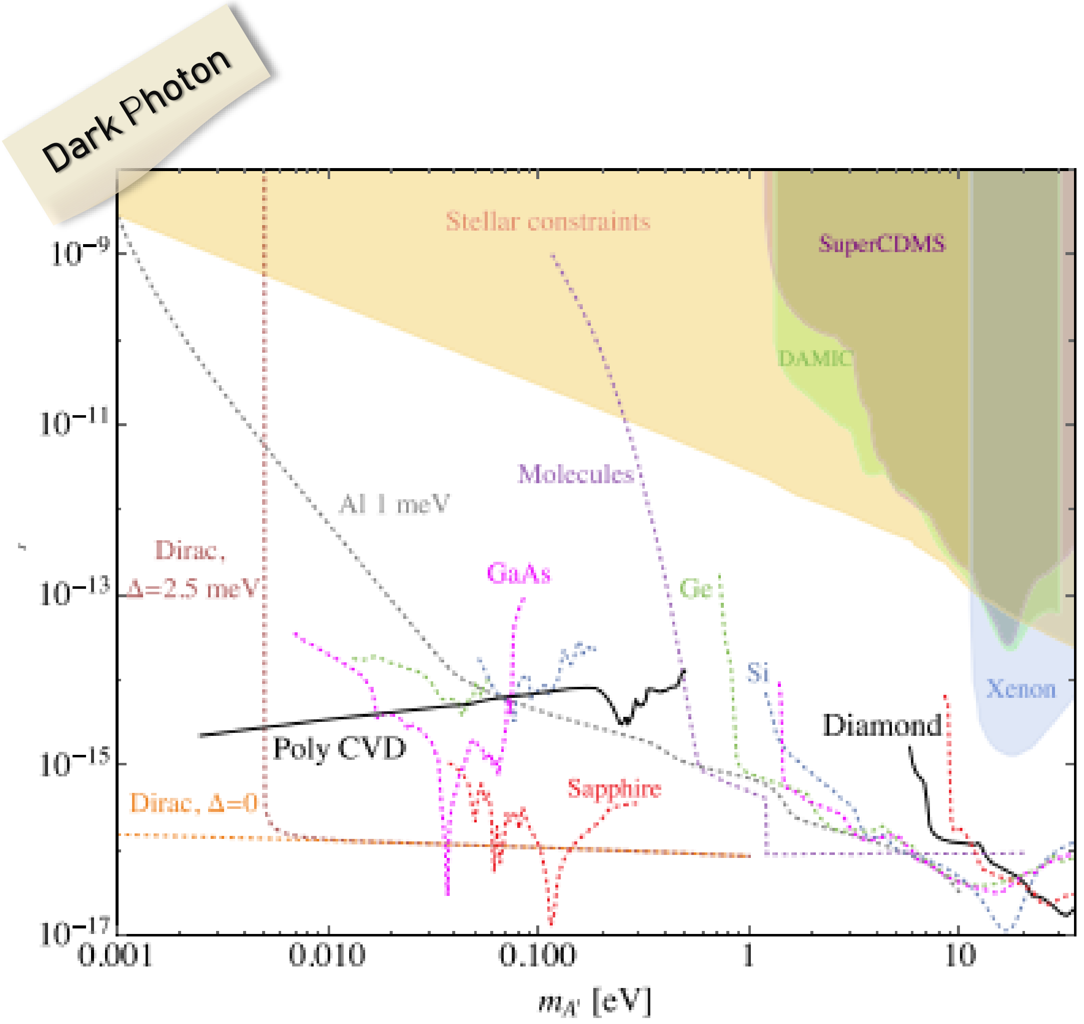


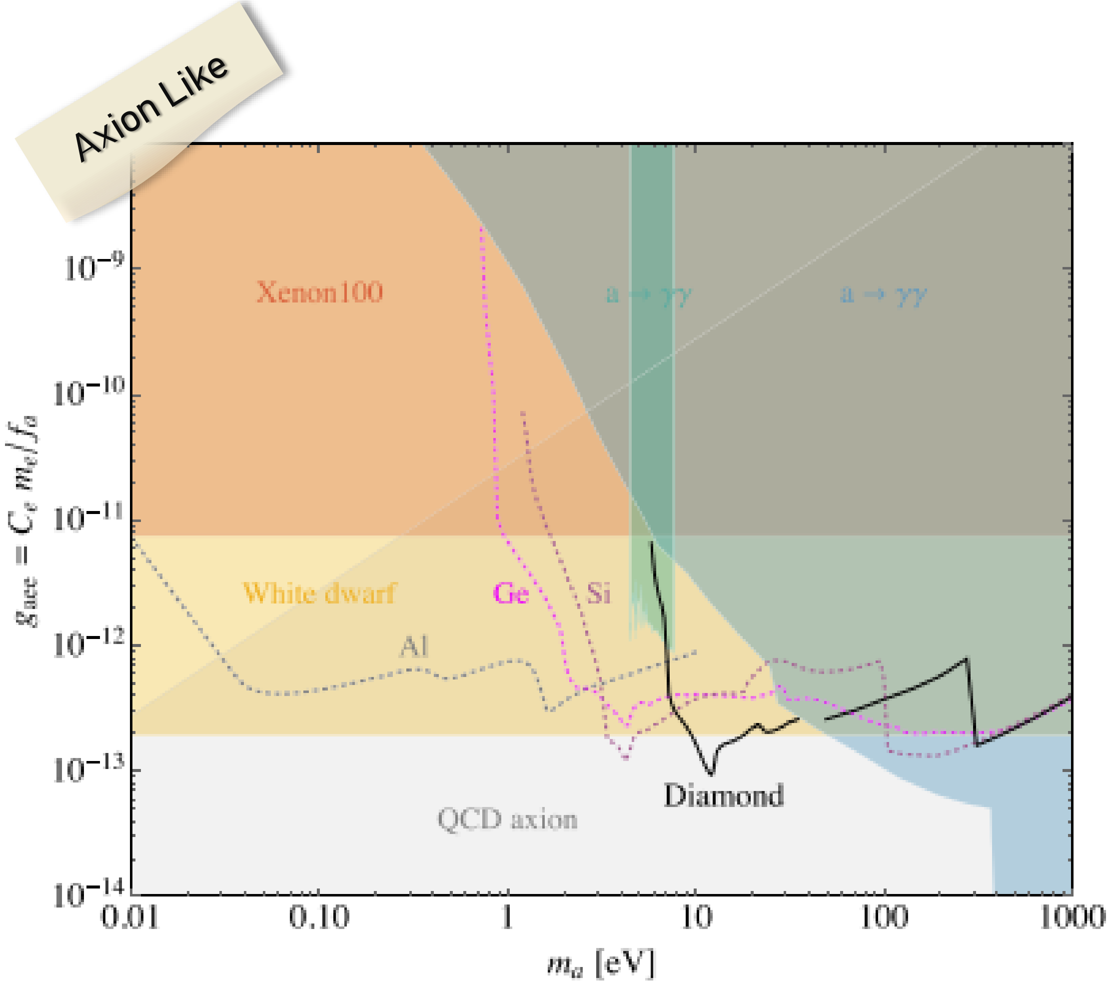


2 e-h pair limit






Dark Photon
Stellar constraints
SuperCDMS
DAMIC
Molecules
Al 1 meV
Dirac,
Δ=2.5 meV
GaAs
Ge
Si
Xenon
Diamond
Poly CVD
Sapphire
Dirac, Δ=0
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
0.001
0.010
0.100
1
10
$m_{A'}$ [eV]


Axion Like
Xenon100
White dwarf
Ge
Si
Al
Diamond
QCD axion
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$g_{aee} = C_e\, m_e/f_a$
0.01
0.10
1
10
100
1000
m_a [eV]

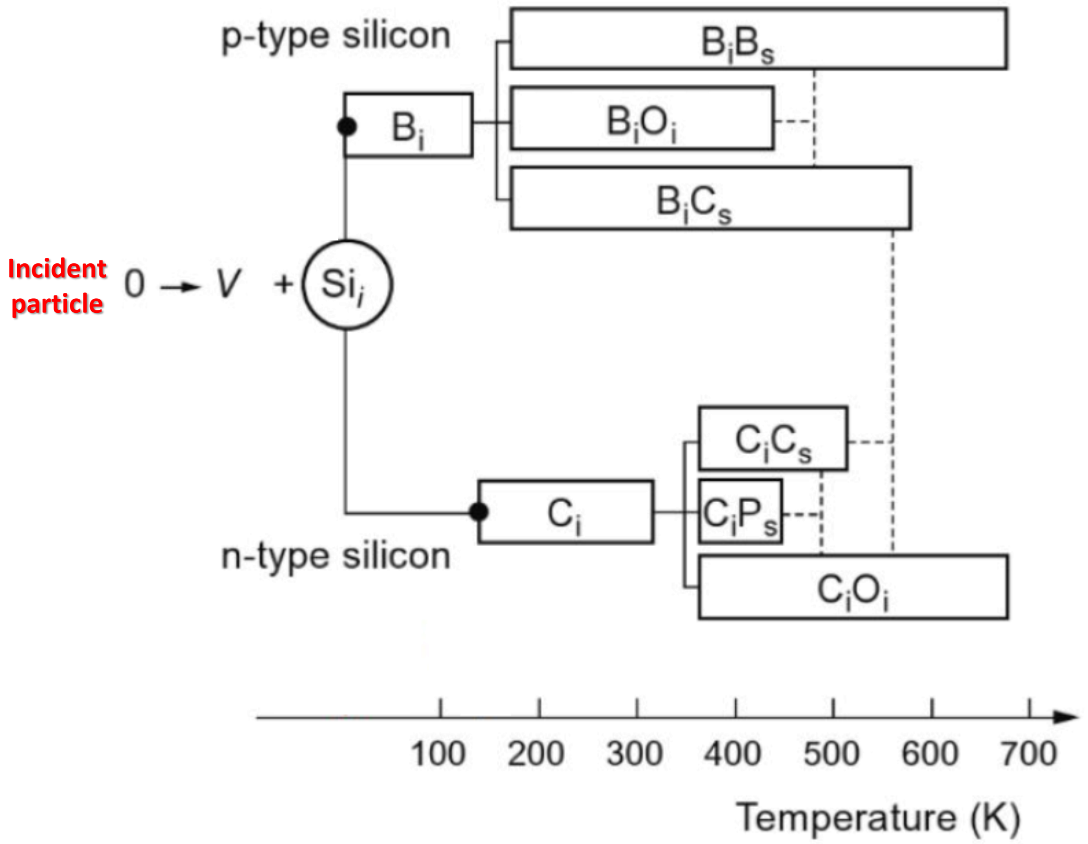
•Radiation Effects I

The Hamburg N_{eff} Model

G. **Lindstrom et al.**, NIM A 466(2001) 308-326
"Radiation damage in silicon detectors"

Radiation damage modeling		
Constant Damage Terms	**Acceptor Introduction**	$\frac{dN_{acc.}^{con.}(t)}{dt} = g_{C_A} \times \Phi_{eq}(\text{t})$
	Donor Introduction	$\frac{dN_{don.}^{con.}(t)}{dt} = g_{C_D} \times \Phi_{eq}(\text{t})$
	Acceptor Removal	$\frac{dN_{acc.}^{rem.}(t)}{dt} = -c_{C_A} \times \Phi_{eq}(\text{t}) \times N_{acc.}^{rem.}(t)$
	Donor Removal	$\frac{dN_{don.}^{rem.}(t)}{dt} = -c_{C_D} \times \Phi_{eq}(\text{t}) \times N_{acc.}^{rem.}(t)$
Short term annealing	Acceptor Reduction	$\frac{dN_{acc.}^{short.}(t)}{dt} = g_A \times \Phi_{eq}(\text{t}) - k_A(T) \times N_{acc.}^{short.}(t)$
Long term annealing	Max Introducible Acceptors	$\frac{dN_{acc.}^{Max.long.}(t)}{dt} = g_Y \times \Phi_{eq}(\text{t}) - k_Y(T) \times N_{acc.}^{Max.long.}(t)$
	Acceptor Introduction	$\frac{dN_{acc.}^{long.}(t)}{dt} = k_Y(T) \times N_{acc.}^{Max.long.}(t)$

Acceptor removal, Defect Kinetics (simplified ☺)



- Incident particle hits silicon atom and created Vacancy (V) and Interstitial Silicon (Si_i)
- Si_i Propagates and can transform substitutional Boron/Carbon to B_i/C_i (interstitial),
- B_i/C_i can form several defects, but the most prominent in high resistivity silicon is:

$$\mathbf{Si_i + B_s \rightarrow B_i + O \rightarrow B_iO_i}$$

or

$$\mathbf{Si_i + C_s \rightarrow C_i + O \rightarrow C_iO_i}$$

Change type of final defects but not amount of active implant

- Since B_i and C_i both compete for the same Si_i, if we introduce more Carbon we would expect to from less B_iO_i defects and more C_iO_i
- If we exchange Boron with a less mobile (heavier) atom (Ga), then we should also enhance C_iO_i defects instead of Ga_iO_i

• Mobility & Trapping

N_{eff} – Dynamic Model

Radiation damage modeling		
Constant Damage Terms	Acceptor Introduction	$N_{acc.}^{con.}(t) = g_{c_A} \times \int_0^t \Phi_{eq.}(\tau)\partial\tau$
	Donor Introduction	$N_{don.}^{con.}(t) = g_{c_D} \times \int_0^t \Phi_{eq.}(\tau)\partial\tau$
	Acceptor Removal	$N_{acc.}^{rem.}(t) = f_{c_A} \times N_{eff.}(0)\left(1 - e^{-c_{c_A}\int_0^t \Phi_{eq.}(\tau)\partial\tau}\right)$
	Donor Removal	$N_{don.}^{rem.}(t) = f_{c_D} \times N_{eff.}(0)\left(1 - e^{-c_{c_D}\int_0^t \Phi_{eq.}(\tau)\partial\tau}\right)$
Short term annealing	Acceptor Reduction	$N_{acc.}^{short.}(t_i) = g_A \times \int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \Big/ \delta t \times \frac{\left(1 - e^{-k_a(T_i)\times\delta t}\right)}{k_a(T_i)} + N_{acc.}^{short.}(t_{i-1}) \times e^{-k_a(T_i)\times\delta t}$
Long term annealing	Max Introducible Acceptors	$N_{acc.}^{Max.long.}(t_i) = g_Y \times \int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \Big/ \delta t \times \frac{\left(1 - e^{-k_Y(T_i)\times\delta t}\right)}{k_Y(T_i)} + N_{acc.}^{Max.long.}(t_{i-1}) \times e^{-k_Y(T_i)\times\delta t}$
	Acceptor Introduction	$N_{acc.}^{long.}(t_i) = N_{acc.}^{long.}(t_{i-1}) + g_Y(T) \times \frac{\int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \Big/ \delta t}{k_Y(T)} \times \left(k_Y(T) \times t + e^{-k_Y(T)t} - 1\right) + N_{acc.}^{Max.long.}(t_i) \times \left(1 - e^{-k_Y(T)t}\right)$

•Sources of Dark Current

Bụľľ Éğğêçţş

Sources of dark current in semiconductors:

- ✓ Generation current (I_g)
- ✓ Trap Assisted tunneling (TAP), Fowler - Nordheim formula
- ✓ Field Assisted tunneling (Pool-Frenkel emission)
- ✓ Impact ionization (E > 15 V / μm)

Effects reducing dark current:

- ✓ Recombination

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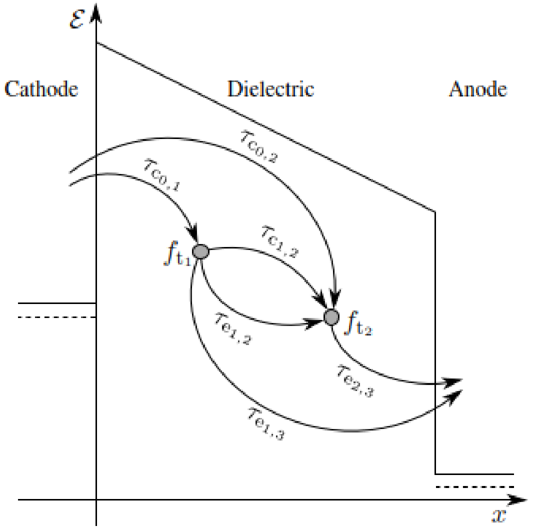
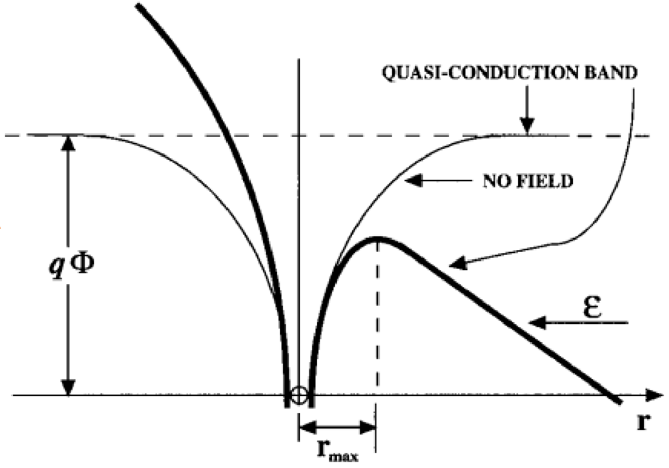
- ➢ Field assisted interface emission (Schottky effect)





•DAMIC-M Design