Silicon Photomultiplier, a new device for low light level photon detection

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Outline

- Concept of a Silicon Photomultiplier
- Advantages
- Problems
- Status of front-illuminated devices
- Development of back-illuminated devices
- Conclusions

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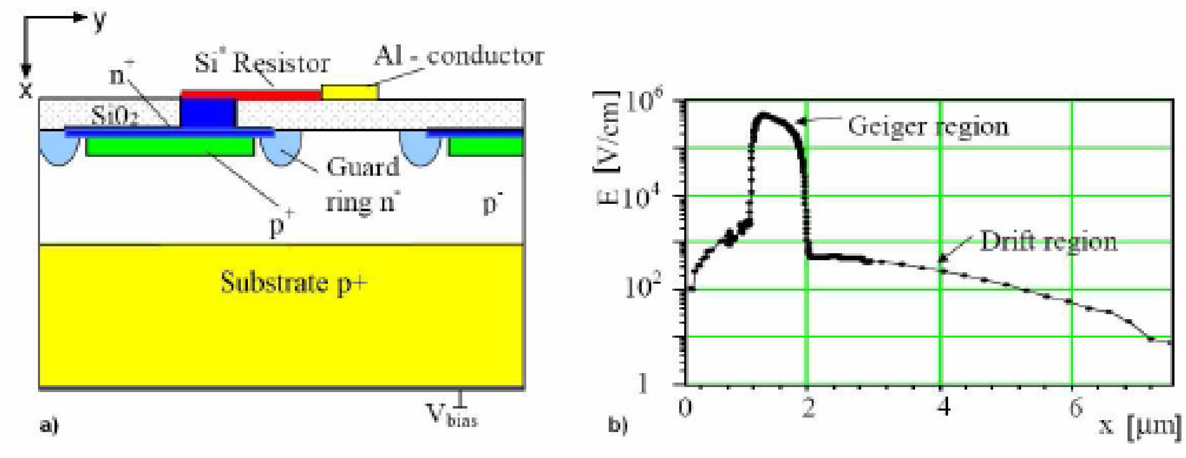
Silicon Photomultiplier

Basic building block: avalanche photodiode operating in Geiger mode



- Device is operated above breakdown voltage
- Photon is absorbed in depleted silicon
- Electron (or hole) drifts into high field region
- Avalanche amplification (Geiger breakdown)
- Signal size (“amplification”) given be overvoltage and cell capacity $Q = C \times \Delta U$ ($> 10^6$)
- Passive quenching by integrated resistor
- Single cell recovery ~ µs (RC time to recharge)

Single SiPM cell: binary signal of fixed size!

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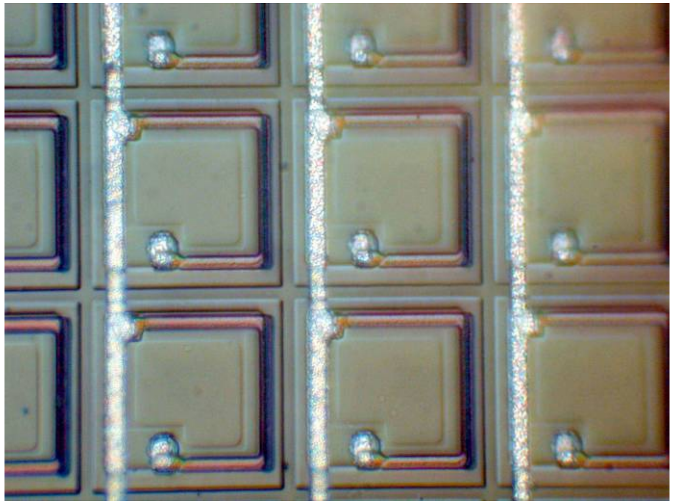
Silicon Photomultiplier

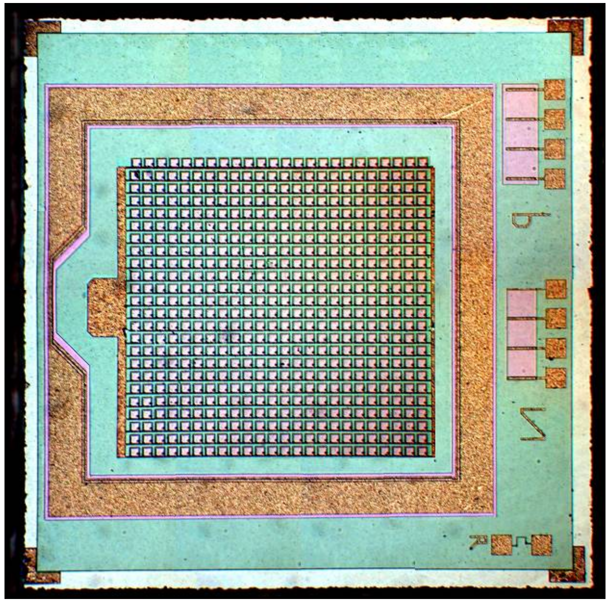
Array of Cells connected to a single output:

Signal = Σ of cells fired

If probability to hit a single cell < 1 => **Signal proportional to # photons**



Pixel size:
~25 x 25 μm^2 to ~100 x 100 μm^2



Array size:
0.5 x 0.5 mm^2 to 5 x 5 mm^2

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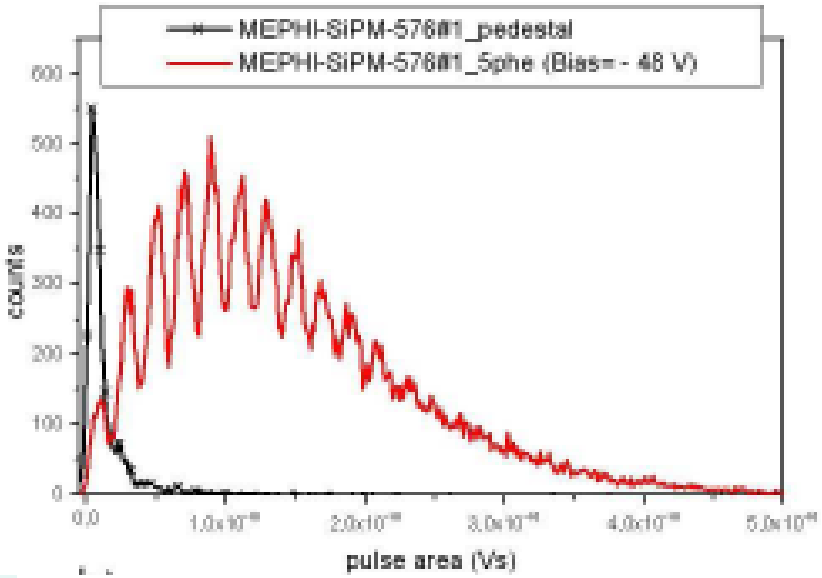
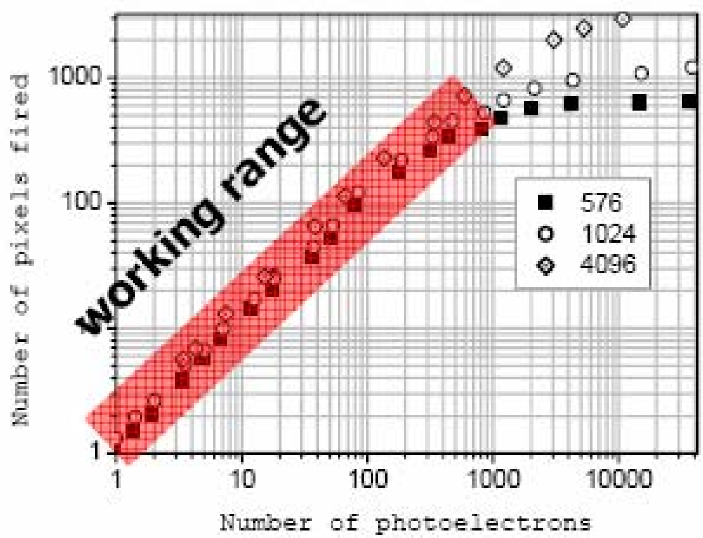
Silicon Photomultiplier

- •Single- & multiphoton peaks
- •“Self calibrating” photon counter”
- •Dynamic range ~ number of pixel
- •Saturation for large signals





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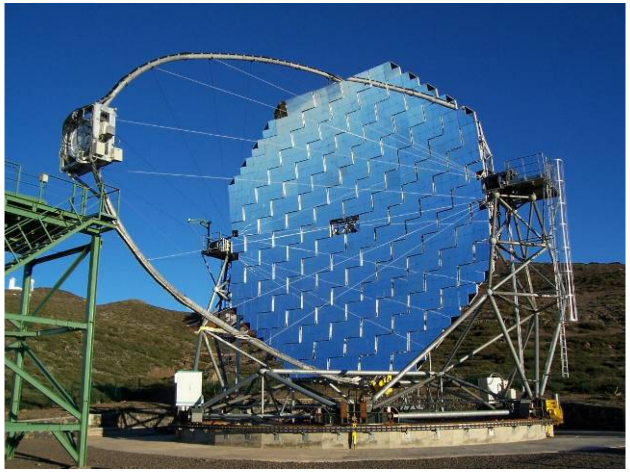
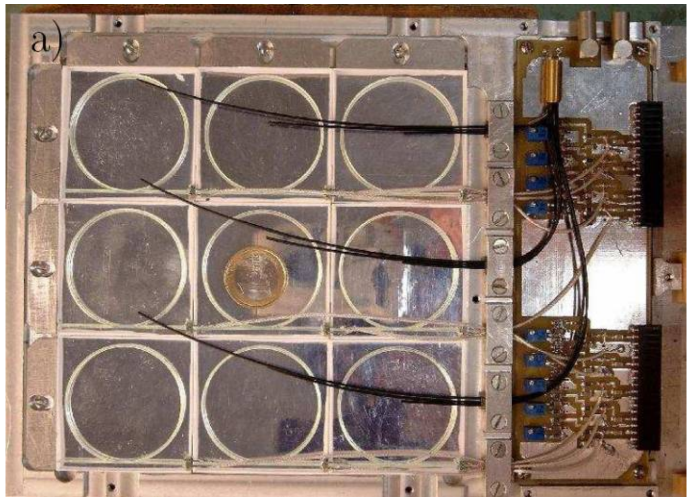
Advantages

- Simple, robust device
- Photon counting capability
- Easy calibration (counting)
- Insensitive to magnetic fields
- Fast response (< 1 ns)
- Large signal (only simple amplifier needed)
- competitive quantum efficiency (~ 40% at 400-800 nm)
- No damage by accidental light
- Cheap (~ 10$/unit)
- Low operation voltage (40 – 70 V)
- Many applications



Magic Camera



Hadron Calorimeter for ILC

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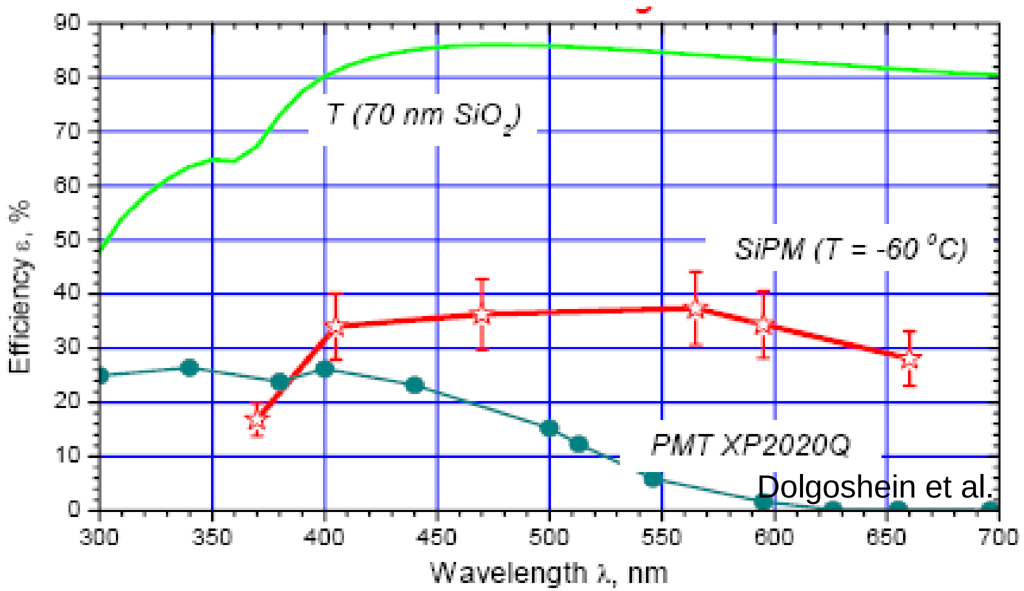
Problems/ R&D issues

- Sensitivity for blue light and UV
- Improve QE to >80%
- Cross Talk
- Dark rate



QE & Fill Factor

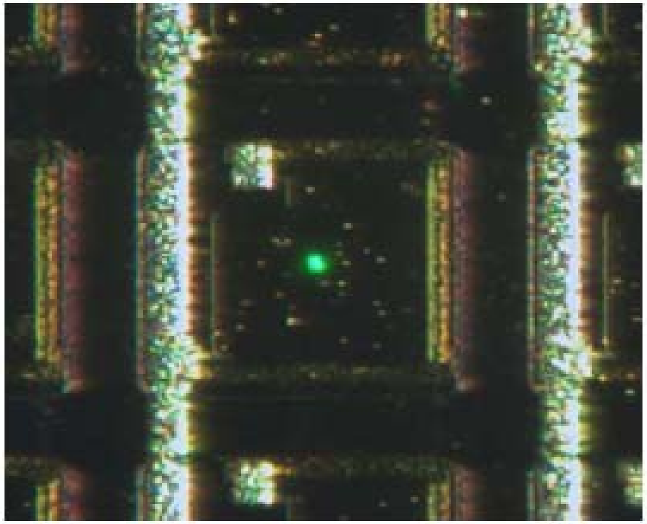
QE = surface transmission
x Geiger efficiency
x geometrical fill factor

Front illuminated devices:

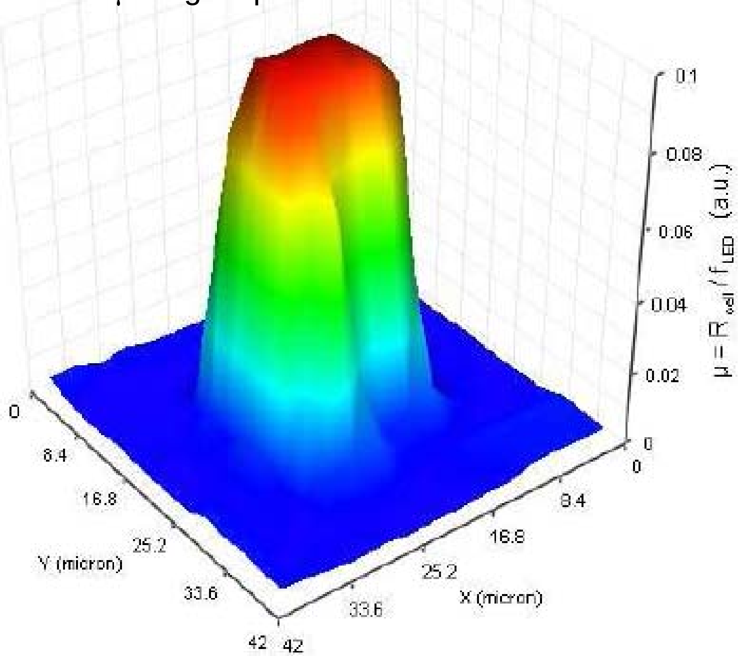
Large area blinded by structures
- Al-contacts
- Resistor
- Guard rings

For 42 x 42 μm^2 device: 15% fill factor

Solutions:
- larger pixel size
- back-Illumination
- (resistive bias layer)



3 µm light spot scanned across device



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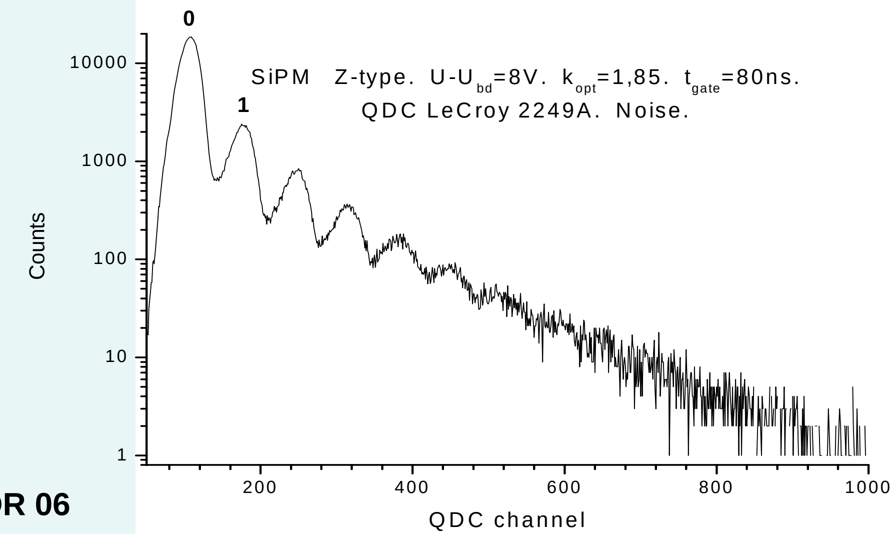
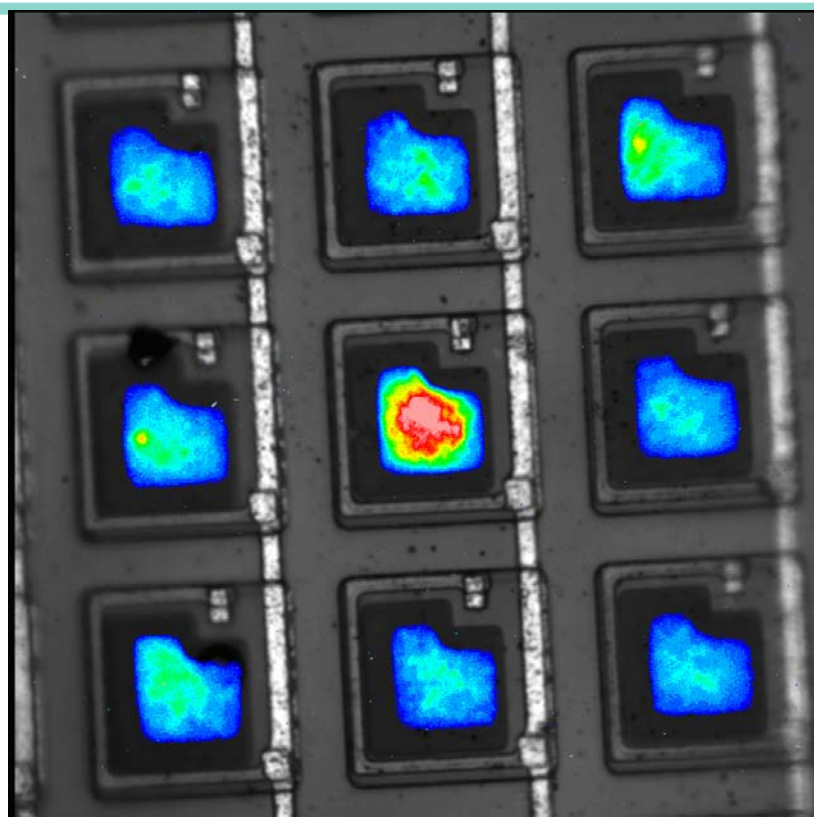
Cross talk

Hot carrier luminescence in avalanches:
~ 1 photon/10^5 carriers
(A. Lacaita, IEEE (1994))

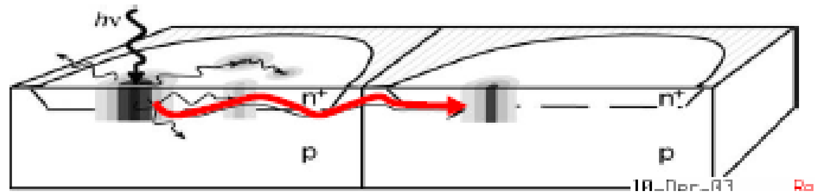
Photons may trigger neighbor cells
> 1 pixel/photon
(excess noise)



Dark counts: Non-poisson distribution



Emission microscope picture



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Problems: Cross talk

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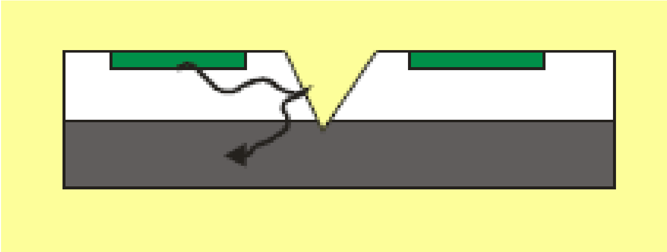
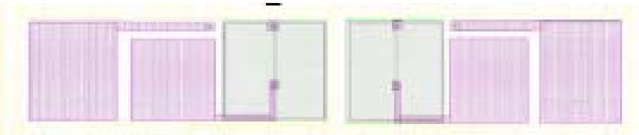
Solutions:

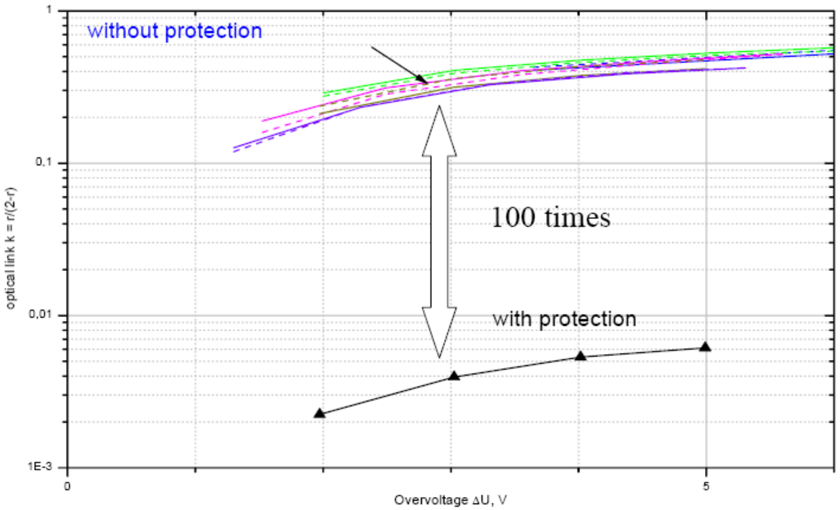
- Lower gain (reduces QE)
- Optical insulation of cell (trenches)



x-talk measurements with special teststructures (MEPhI/Pulsar)



x 100 suppression possible



blue/UV sensitivity

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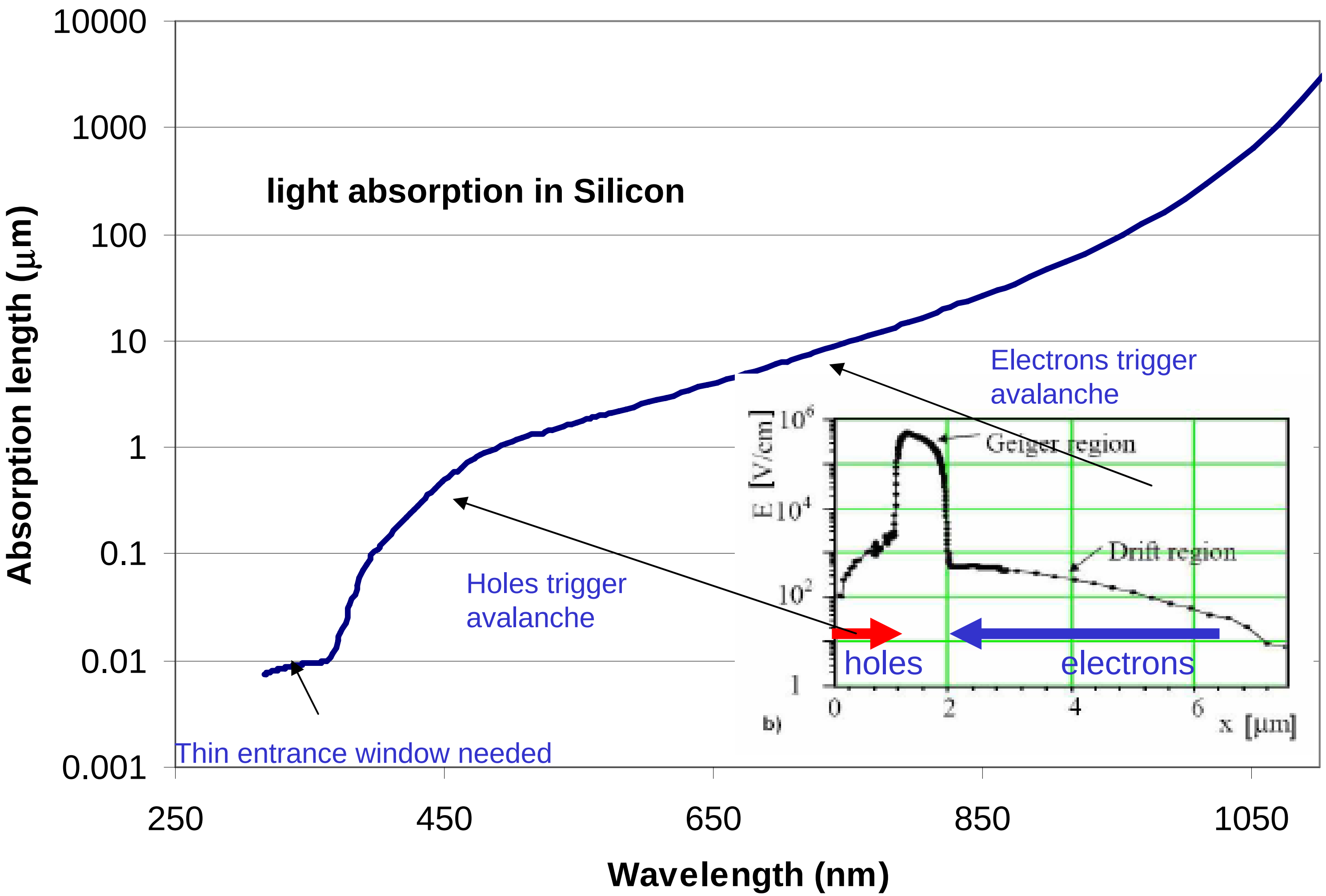

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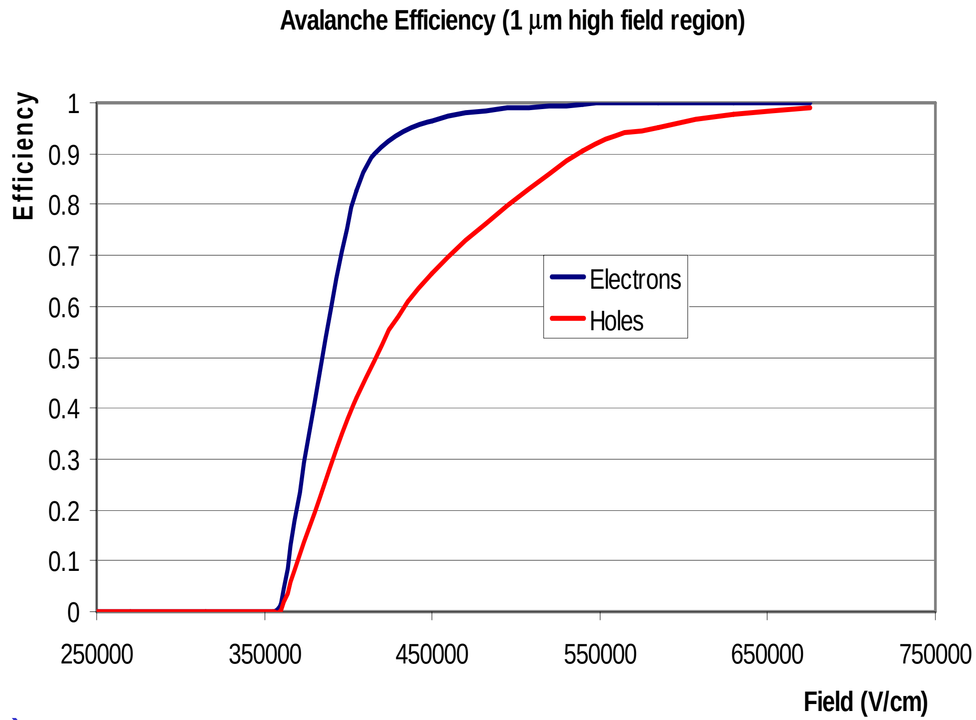
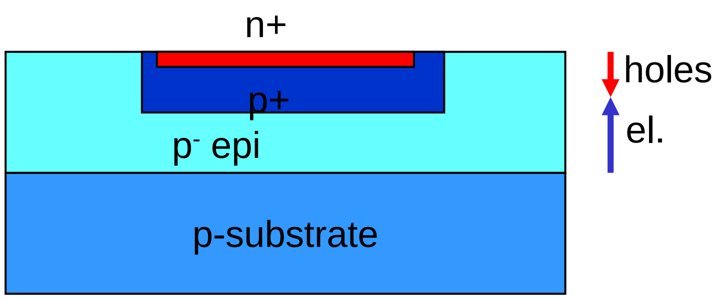
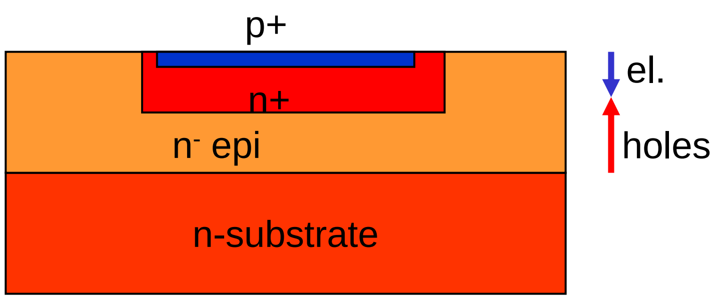
Problems: blue/UV sensitivity

Electrons have a higher probability to trigger an avalanche breakdown then holes



Solutions:
-Increase overvoltage
-Inverted structures
(prototypes produced at MEPhI/Pulsar)





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Problems: Dark Rate

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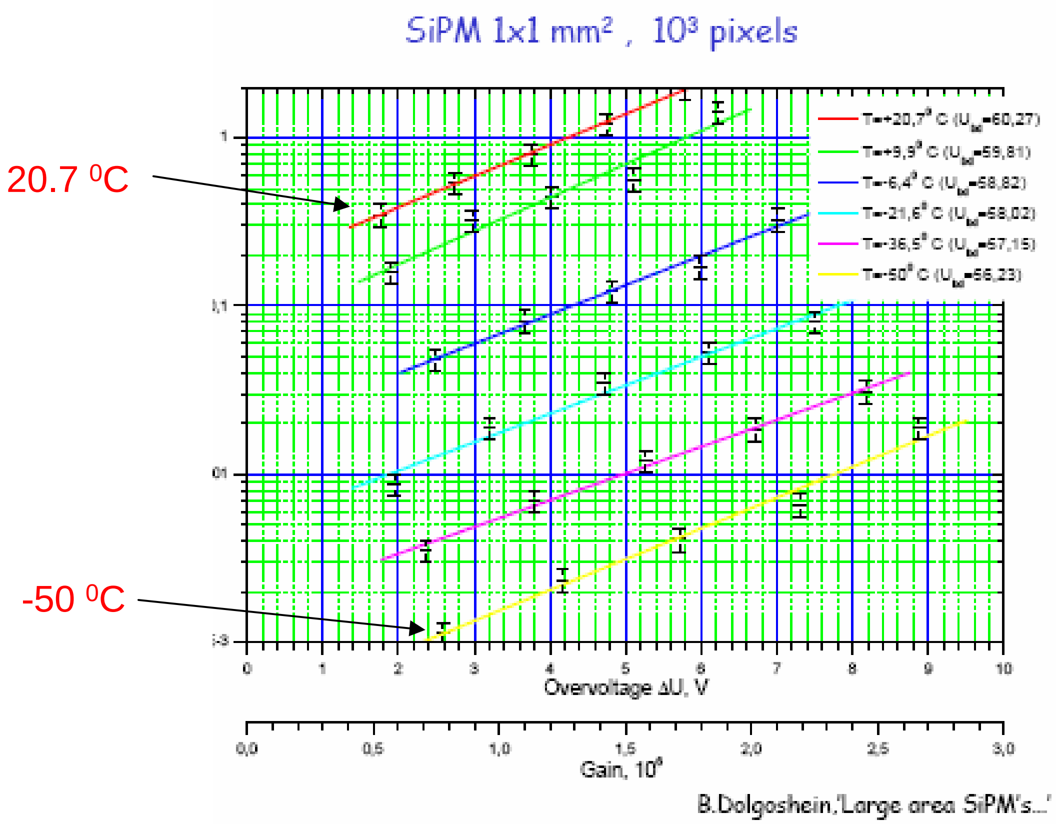
Thermally generated currents: Dark Rate

- Increases with overvoltage/gain (larger depleted area; tunneling)

- problem for large area devices (~50 MHz for 5x5 mm^2 at room temp.)

- cooling helps (but beware of afterpulsing due to trapping)



Optimization Matrix

Optimization of many parameters possible. Depends on applications

	Pixel Size	Overvoltage	trenches
QE	+ Better fill factor	+ Better geiger efficency	- Reduced fill factor
UV response		+ Better geiger efficency (holes)	
X-talk	+ Larger gain	+ Larger gain	- Optical insulation
Dynamic range	- Less pixel		
Dark rate		+ Increase currents	+(?)
Gain	+ Larger capacitance	+ $Q = C \times \Delta U$	

There are cross correlations:
e.g. trenches reduce x-talk, which allows to increase the overvoltage improving QE and UV response

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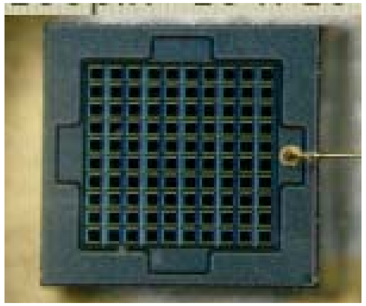
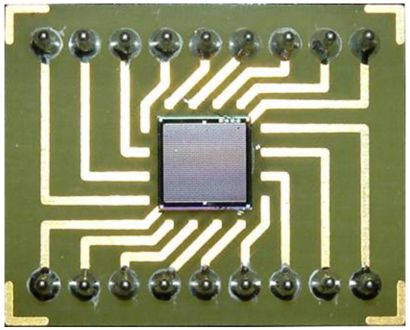
Overview

SiPMs are produced (but not necessarily commercially available) by:

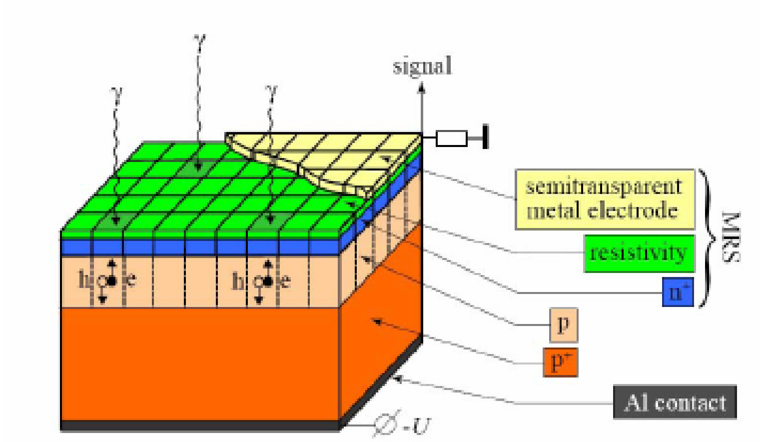
- **CPTA** Moscow
- **MEPhI/Pulsar**, Moscow
- **Dubna/Micron** (MSR, Metal Resistive Layer)
- **Hamamatsu**, Japan (“MPPC”): 1 x 1 mm^2 100 – 1600 pixel (100 mm – 25 mm)
- **SensL**, Irland: 1x1 mm2, ?? pixel



Hamamatsu MPPC
1 x 1 mm^2, 100 pixel



MEPHi/Pular
5 x 5 mm^2, 2500 pixel



Dubna MSR

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New concept: backside illuminated SiPM

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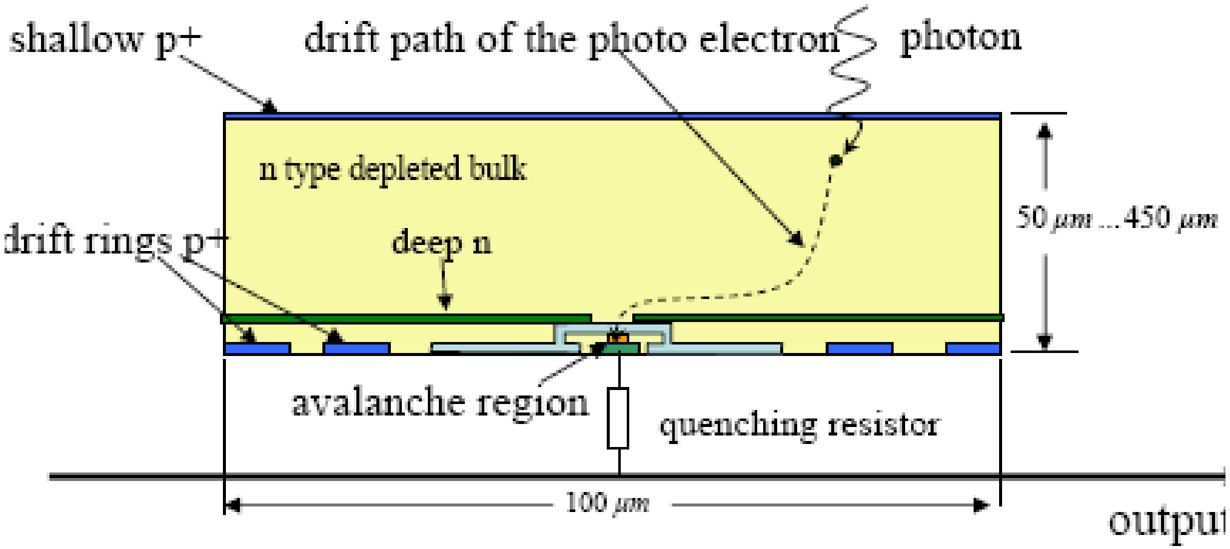
Photons enter through unstructured backside

Lateral drift field focuses electrons into small geiger region



Developed & (to be) produced at MPI Semiconductor Laboratory, Munich

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Backside Illuminated SDD

Advantages:

- Unstructured thin entrance window
- 100% fill factor
- High conversion efficiency (especially at short wavelength)
- Lateral drift field focuses electrons into high field region
- High Geiger efficiency (always electrons trigger breakdown)
- Small diode capacitance (short recovery, reduced x-talk)

Expect high QE (>80%) in large wavelength range (300 nm-1000nm, depending on engineering of entrance window)

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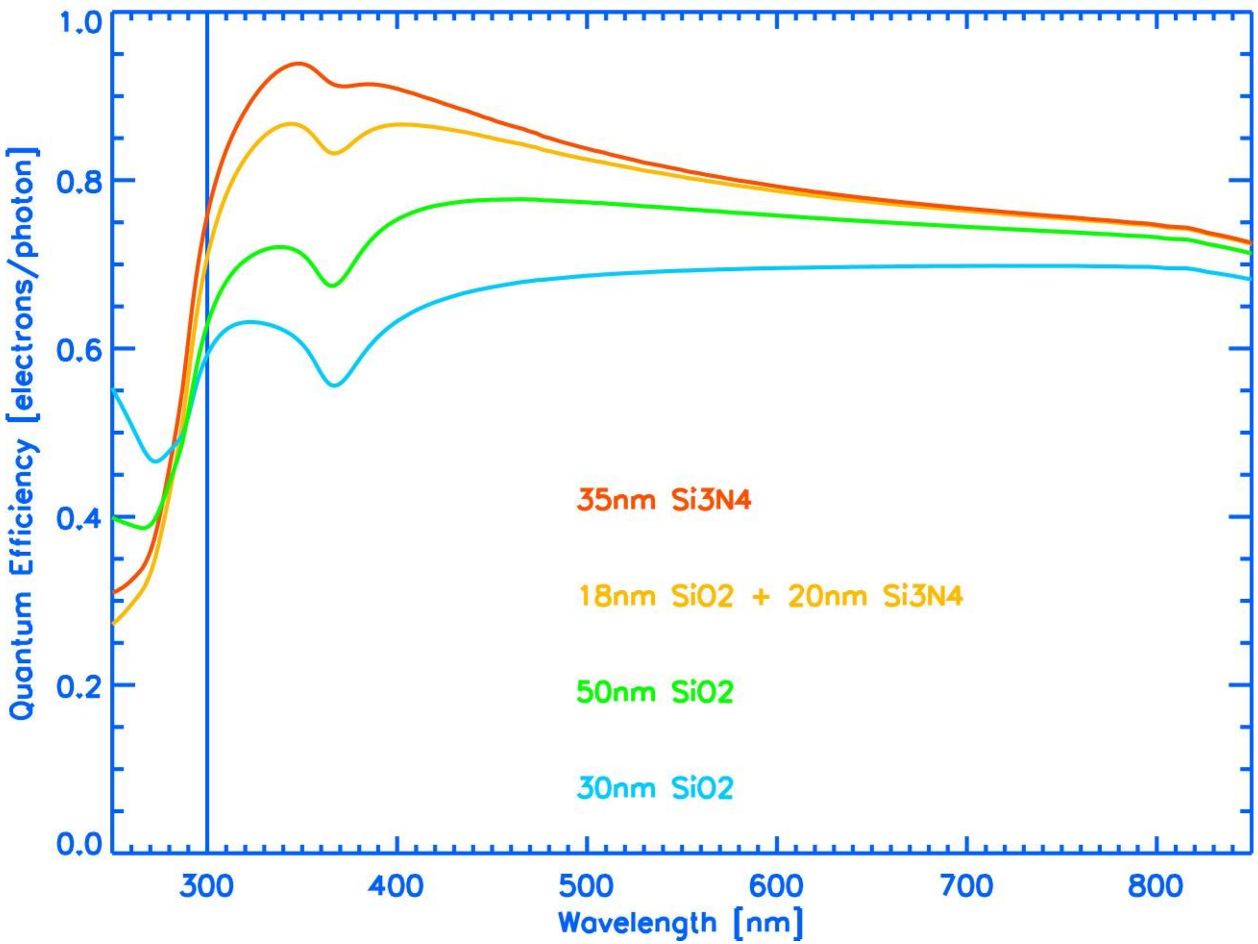
Engineering of Entrance Window

UV-enhanced Anti-Reflective-Coatings (ARC)



(Calculation: R. Hartmann)

Backside Illuminated SDD

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Disadvantages:

- Large volume for thermal generated currents (increased dark rate)

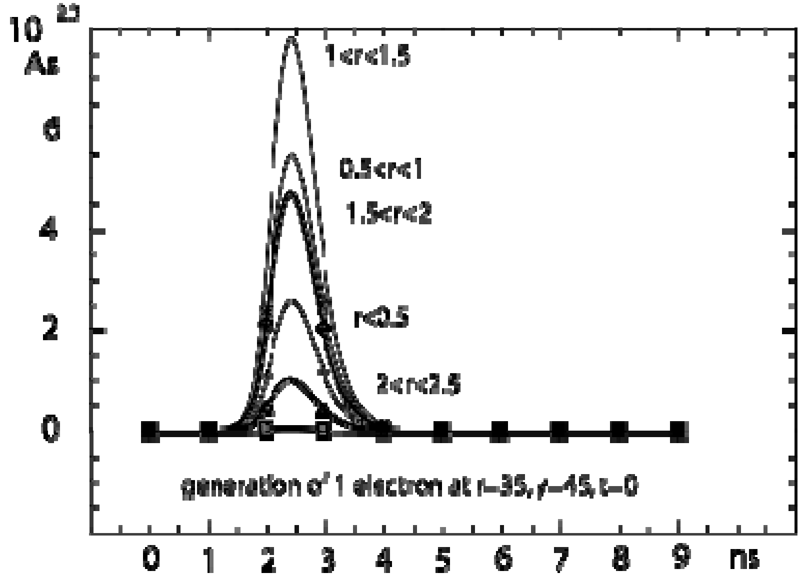
  Maintain low leakage currents
  Cooling
  Thinning (< 50 µm instead of 450 µm)

- Large volume for internal photon conversion (increases x-talk)

  Lower gain (small diode capacitance helps)
  Thinning

- Electron drift increases time jitter

  Small pixels,
  Increased mobility at
  low temperature
  <2 ns possible



Project Status

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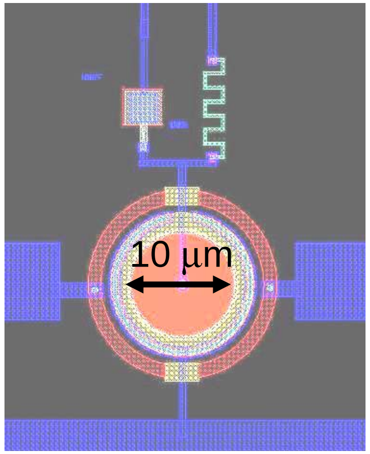
First test structures have been produced
at the MPI semiconductor lab

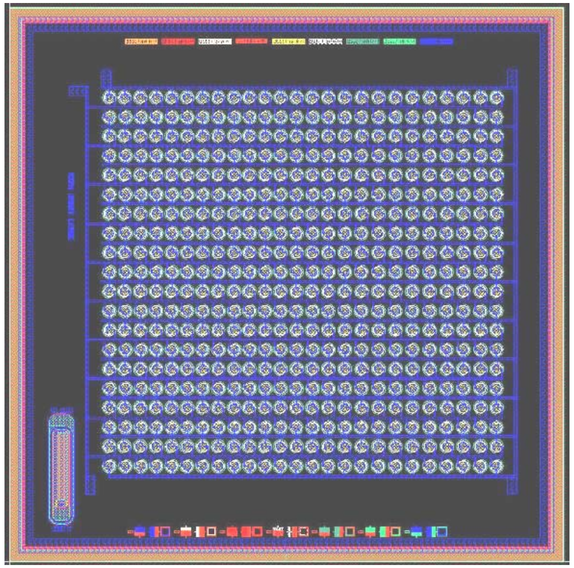
Evaluation (proof of principle) ongoing

“Real” prototypes to be produced 2006/2007

Final devices planned to be used in MAGIC upgrade



Single cell with resistor and
Coupling capacitor



400 pixel array

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Conclusions

SiPM are a novel detector for low level light detection

- photon counting capability
- simple, robust
- easy to operate
- cheap

Ongoing R&D to improve:

- cross talk (trenches,…)
- UV/blue sensitivity (inverted structures,…)
- QE (backside illumination,..)

Will replace photomultiplier tubes in many applications
- see ILC session (CALICE)