Hybrid photon counting and ranging APD array

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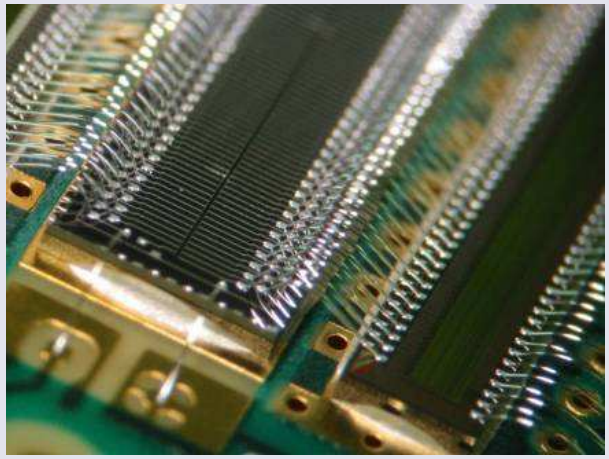
Challenge addressed

- **In this paper we present the concept, design and results of a hybrid combination of:**

- **a 128 linear APD detector array**
- **and 2 Silicon ROIC**
- **realizing**



→15 bit photon counting mode

→15 bit distance ranging, by counting, with clock period resolution (100MHz)
→increased accuracy distance ranging accuracy by analog interpolation, to 150ps (2cm)

outline

- **SPAD background**
- **Brief specifications**
- **Pixel features**
- **ROIC and detector design**
- **Performance & Measurements**
- **Conclusions and perspectives**

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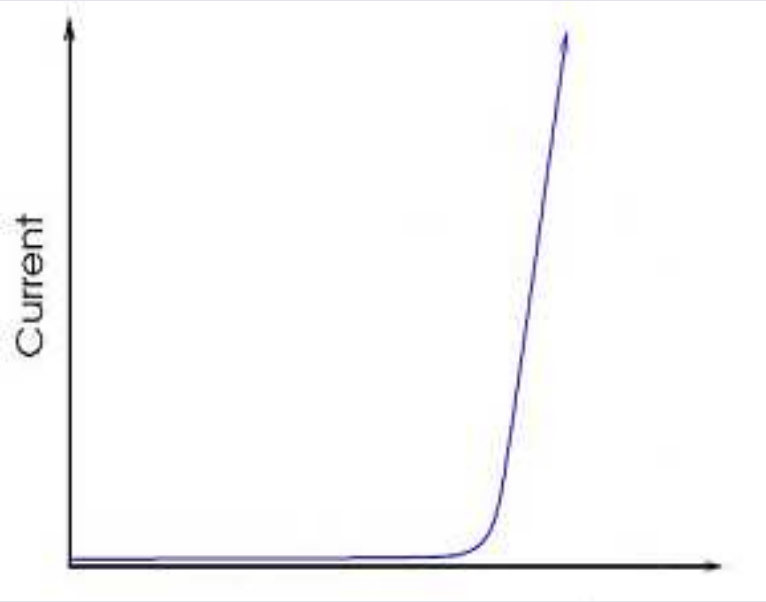
SPAD background

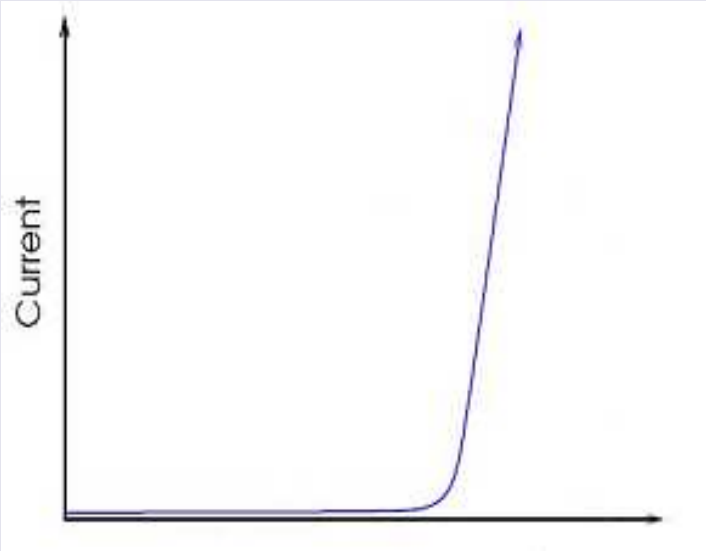
- **SPADS or "Geiger-Mode" APD**
  - APD designed to operate beyond breakdown voltage



- **In this case**
  - it is a silicon detector for visible light
  - breakdown voltage is about 28 V

SPAD background

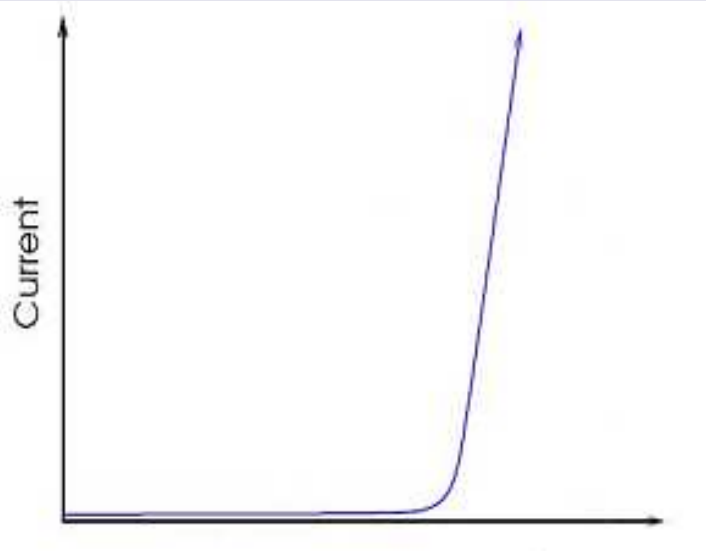
- **SPAD operation:**
  - RESET:
  - APD is brought to *higher than breakdown* bias voltage



  - Electric field is high
  - initial electron is required to initiate the avalanche breakdown

SPAD background

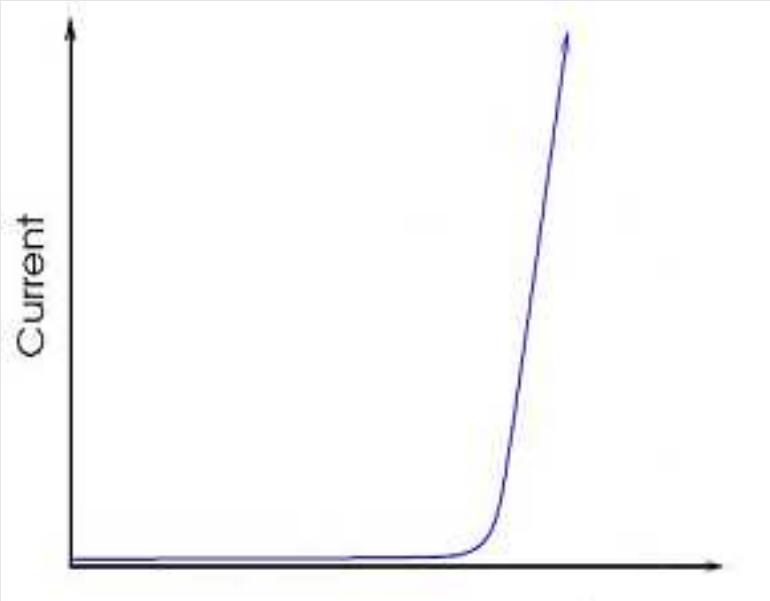
- **SPAD operation: Sensing**
  - An electron is generated in the depletion region due to photoelectric effect (or dark current)



  - The avalanche starts, the APD is going into breakdown

SPAD background

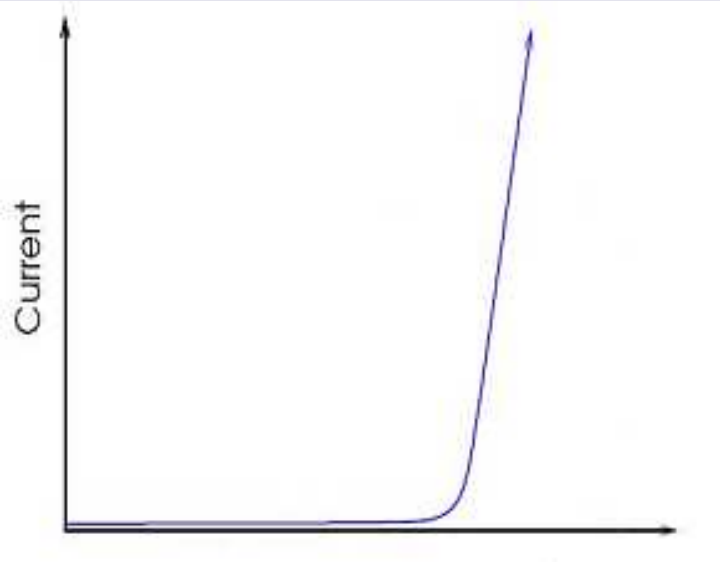
- **SPAD operation: Sensing (2)**
  - Current increases dramatically
  - The bias voltage drops rapidly due to resistive load of external circuit



  - That voltage drop is sensed by the ROIC sense amplifier

SPAD background

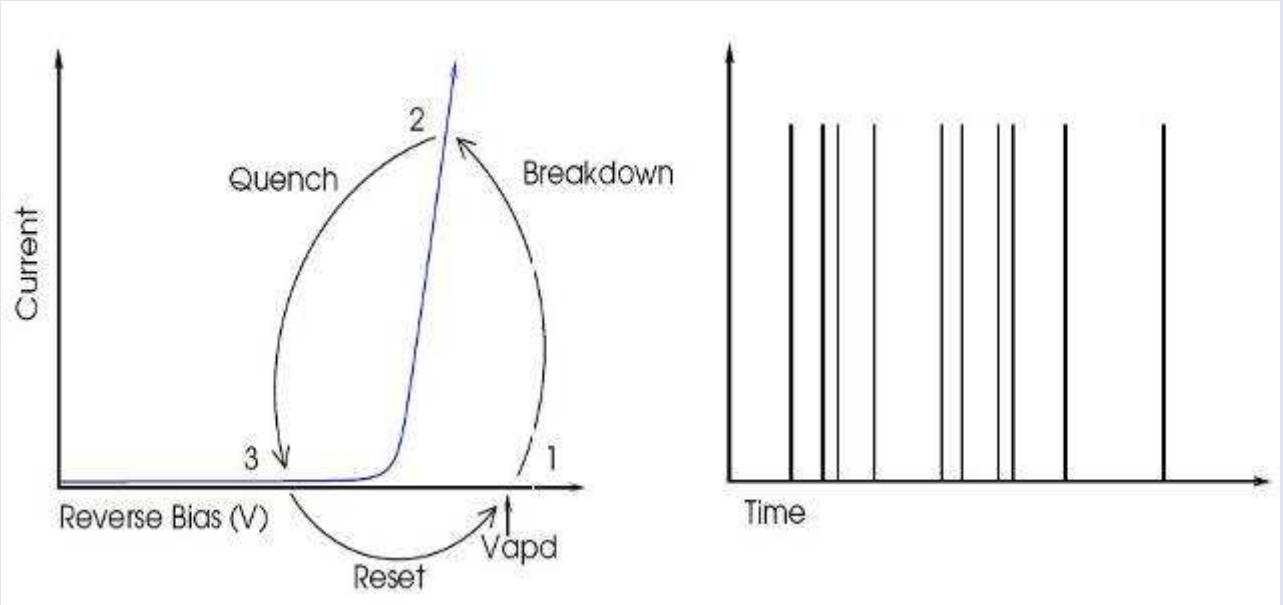
- **SPAD operation: Active Quenching**
  - After breakdown one must “quench” the diode



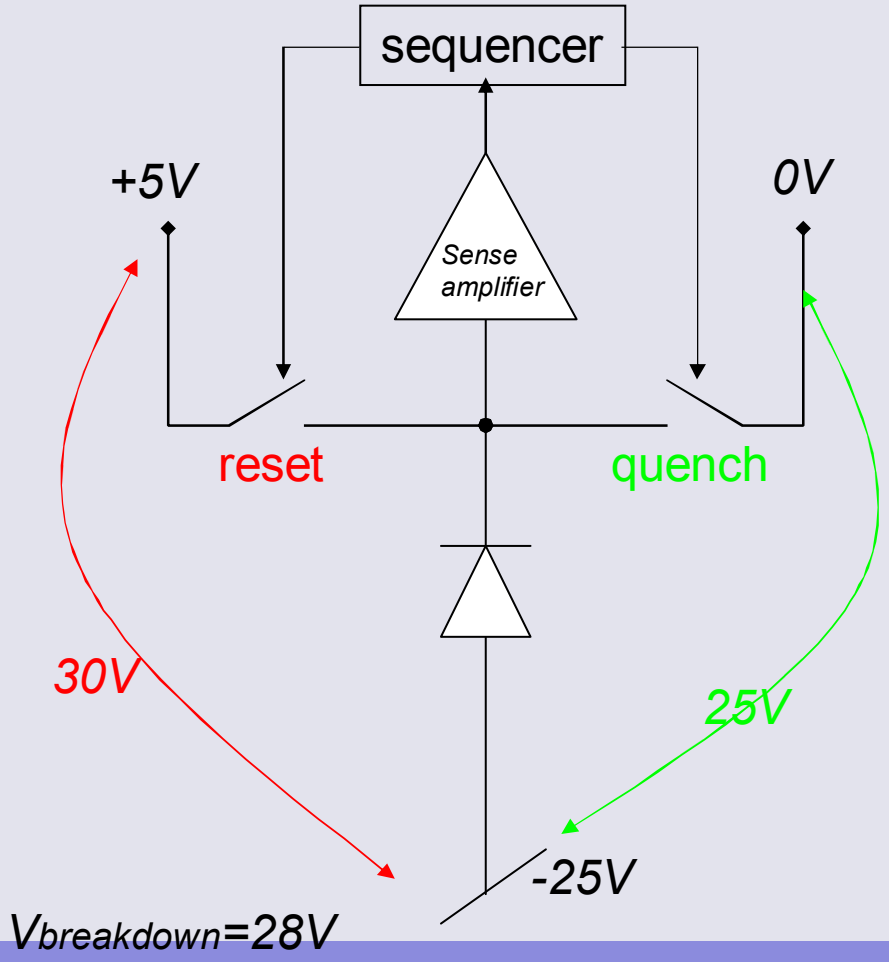
  - The quenching operation makes sure that no residual free charge is present, thus allows the next reset to happen

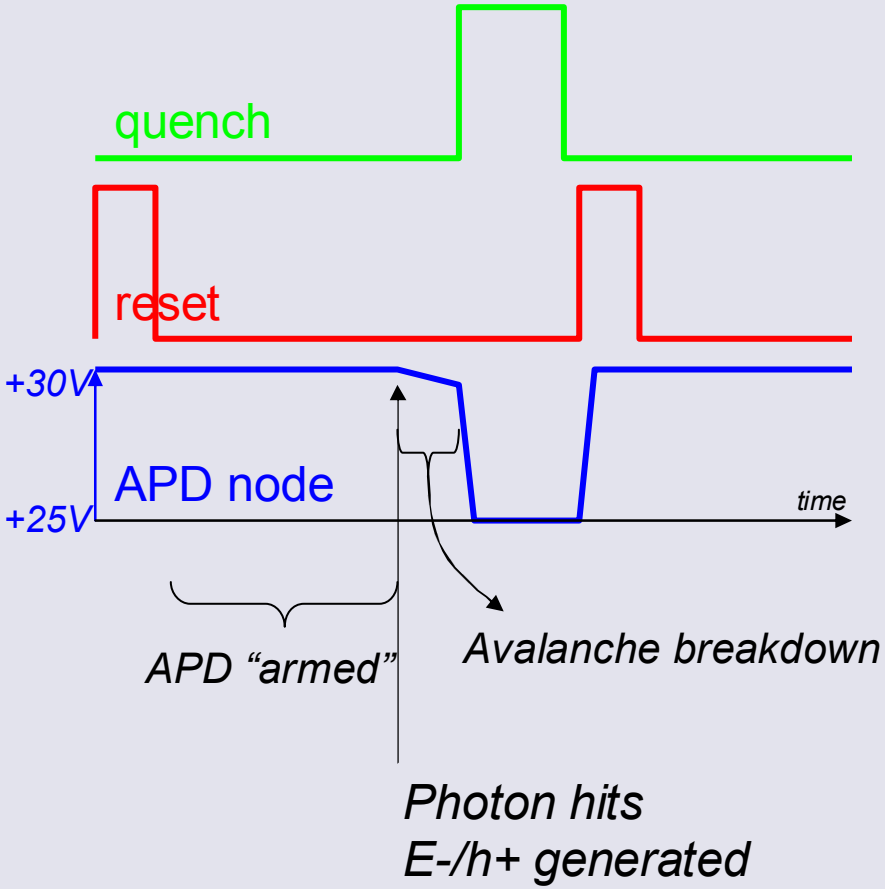
SPAD background

- **Summary**



active quench/reset





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- Pixel features
- ROIC and detector design
- Performance & Measurements
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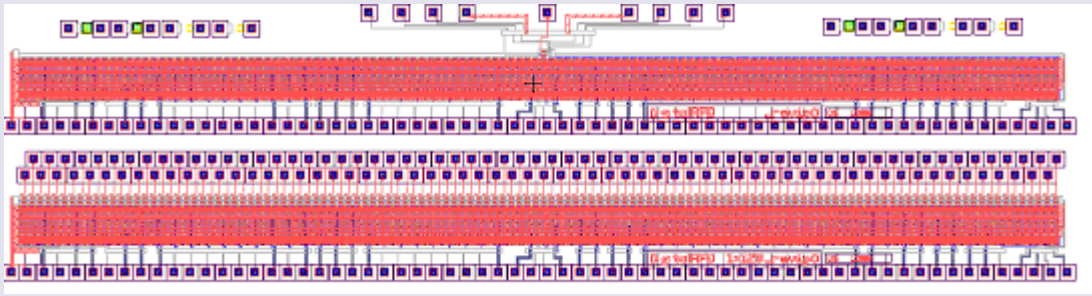
Specifications

- **Scalable ROIC design**



- Pixel pitch: 100um
- 479T per pixel
- 15bits counter in-pixel

- Geiger mode, up to 20MHz count frequency, *(APD limited)*
- Ranging mode, 100MHz timer/counter

- Ranging time accuracy: 150ps
- Analog interpolation for ranging

- Power dissipation 100~150 mW on 128x1 device, depending on mode

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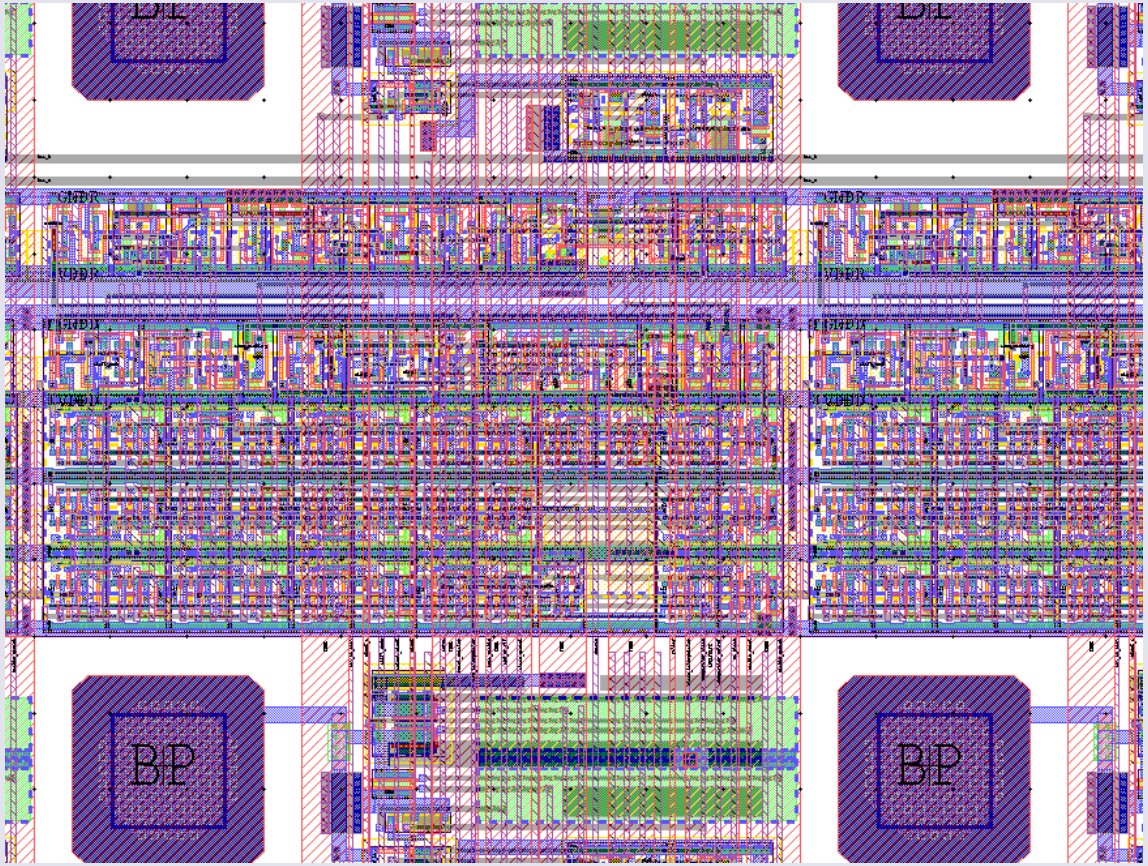
Pixel design

- **Mixed mode pixel**
- **100x100um**
- **479 MOSFETs**



Pixel design

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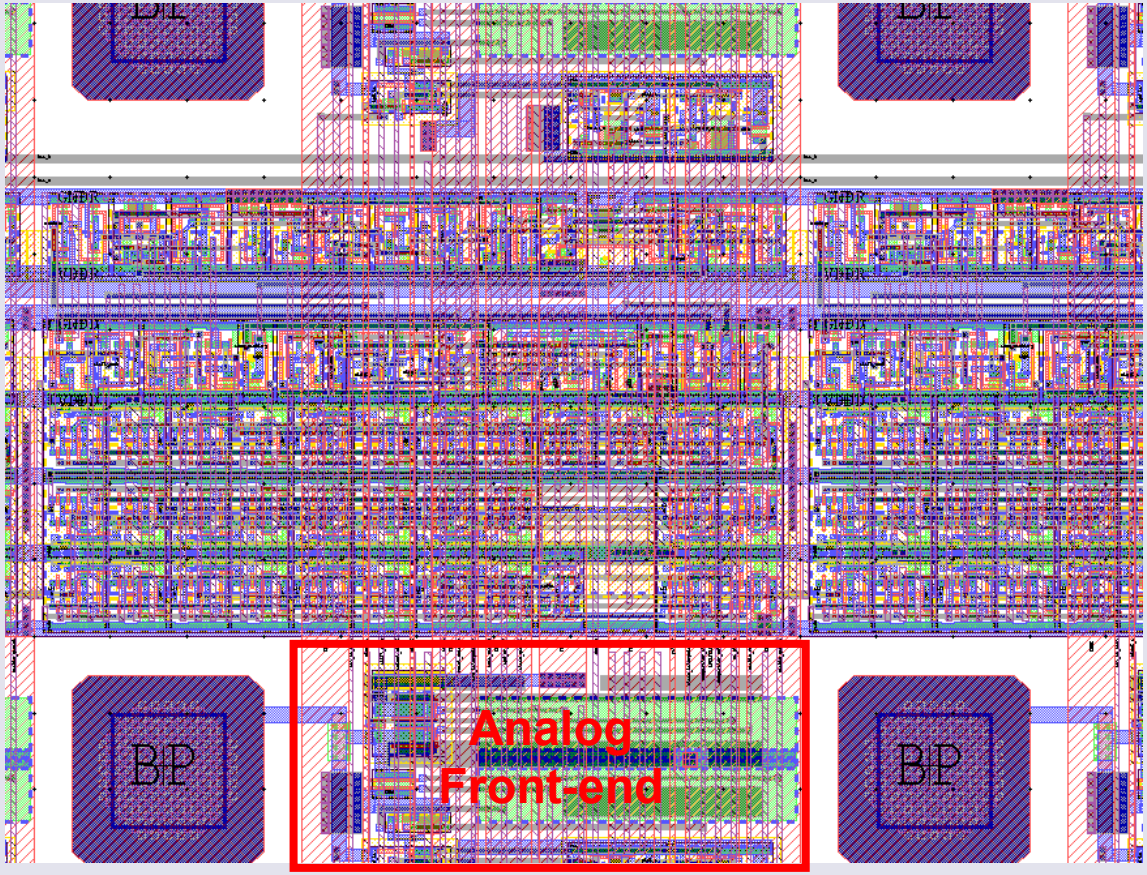

Pixel design

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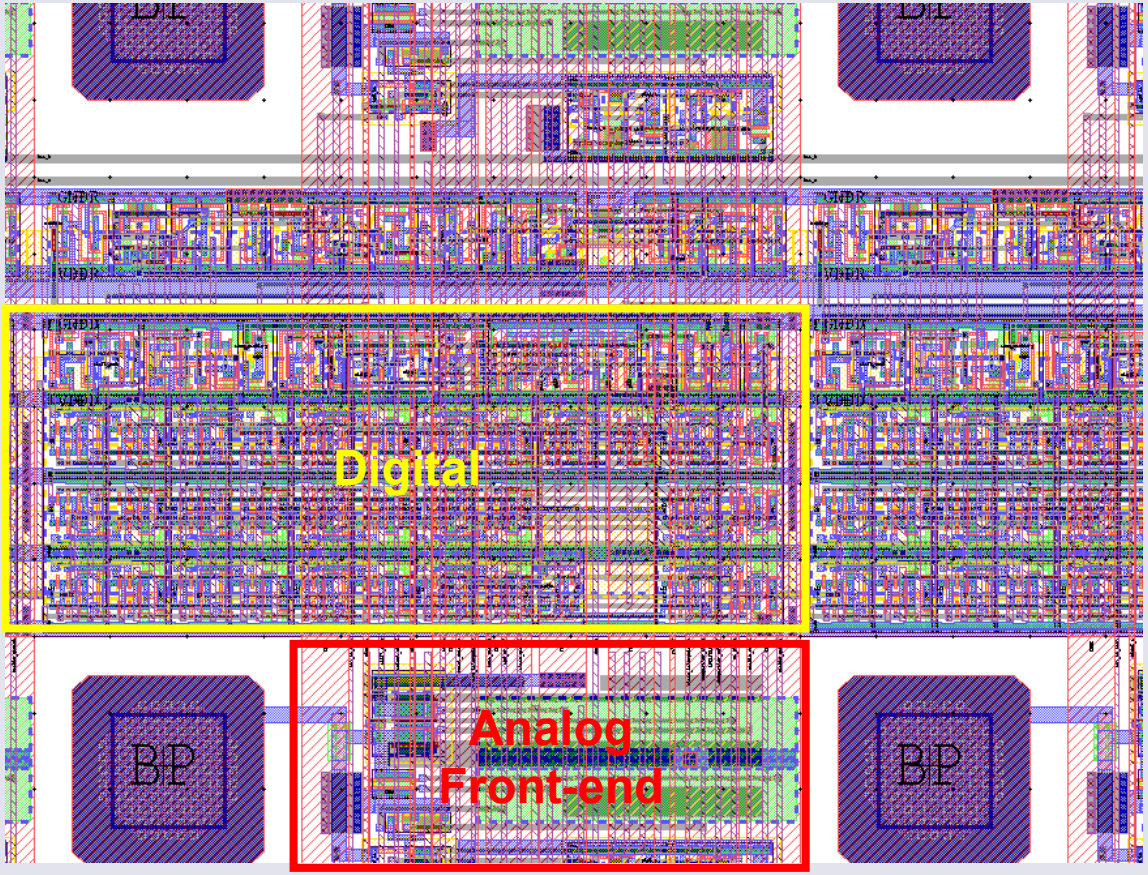

Pixel design

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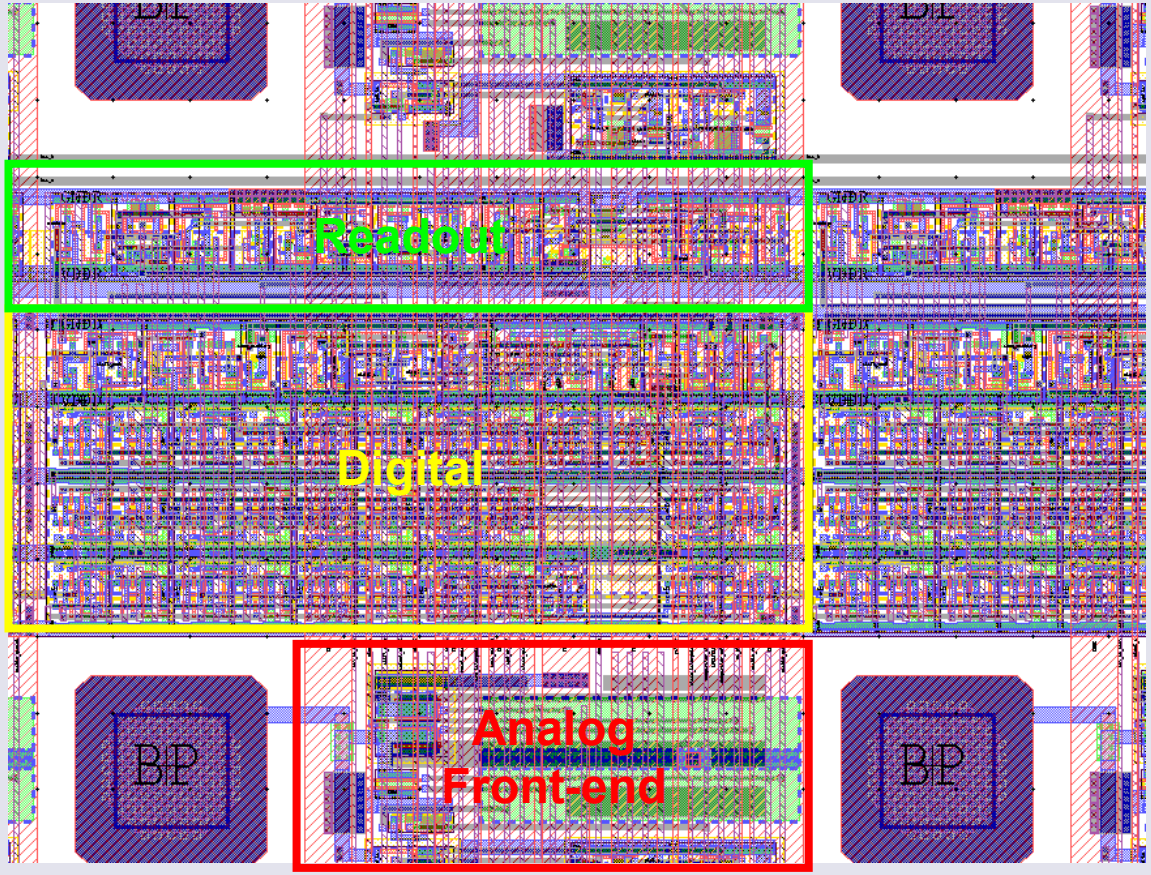
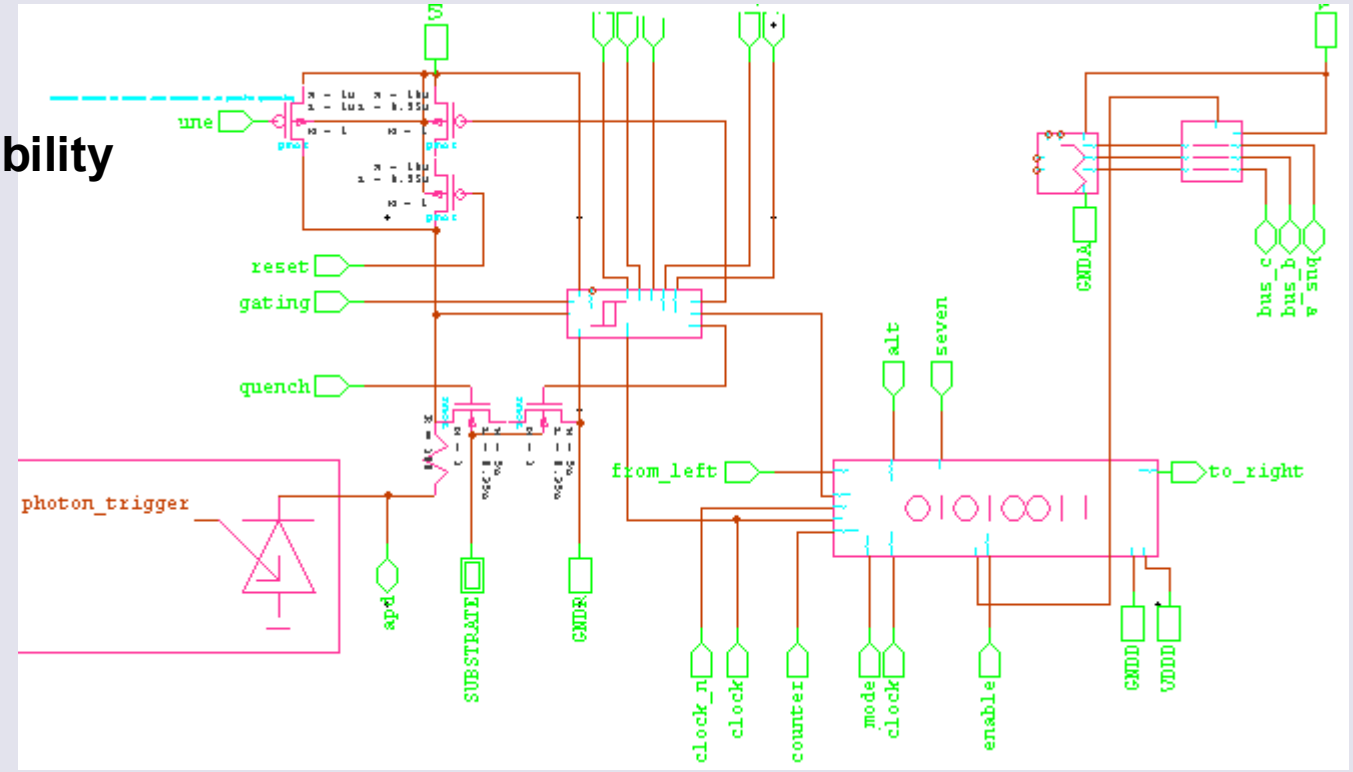


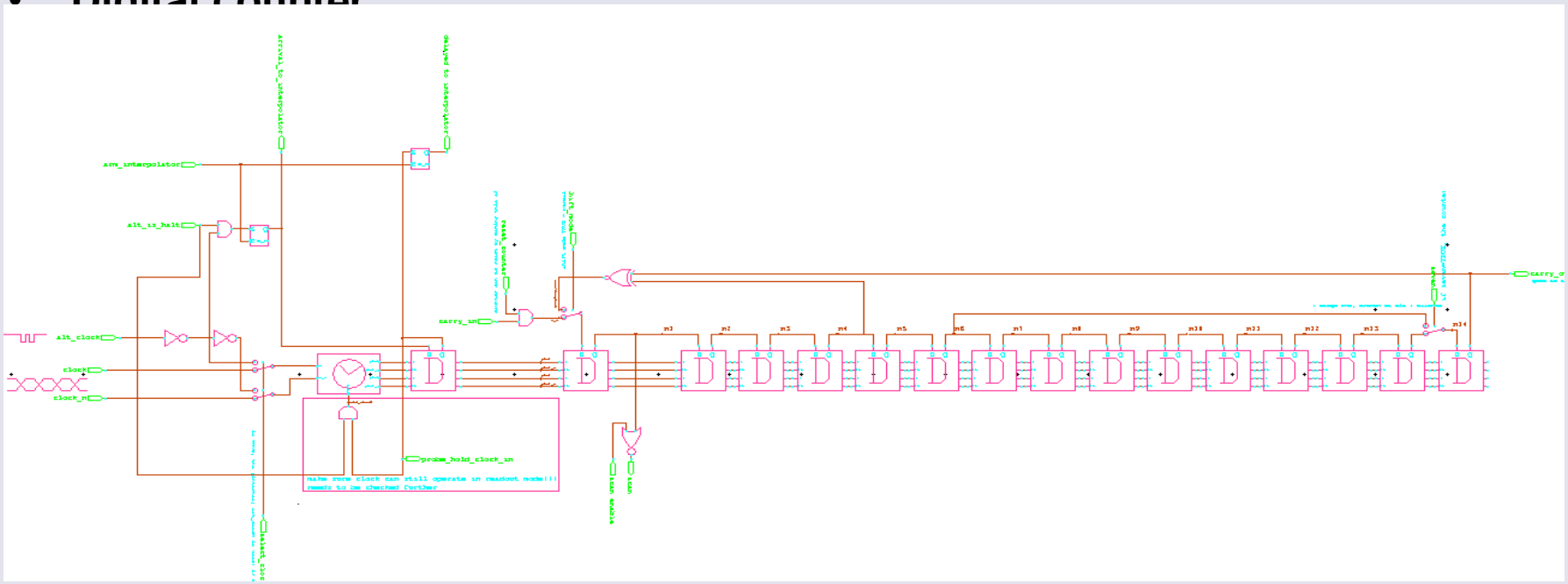
Pixel design

- **Pixel schematic**
- **High degree of programmability**



Pixel design

- **Digital counter**



- Low power consumption, High count rate
- Designed for long Time of Flight, max 5.000m distance
- 100MHz counter = 10 ns TOF accuracy
- higher accuracy by analog interpolation between counts

Pixel design

- **Digital counter Pseudo Random Code, verification example**

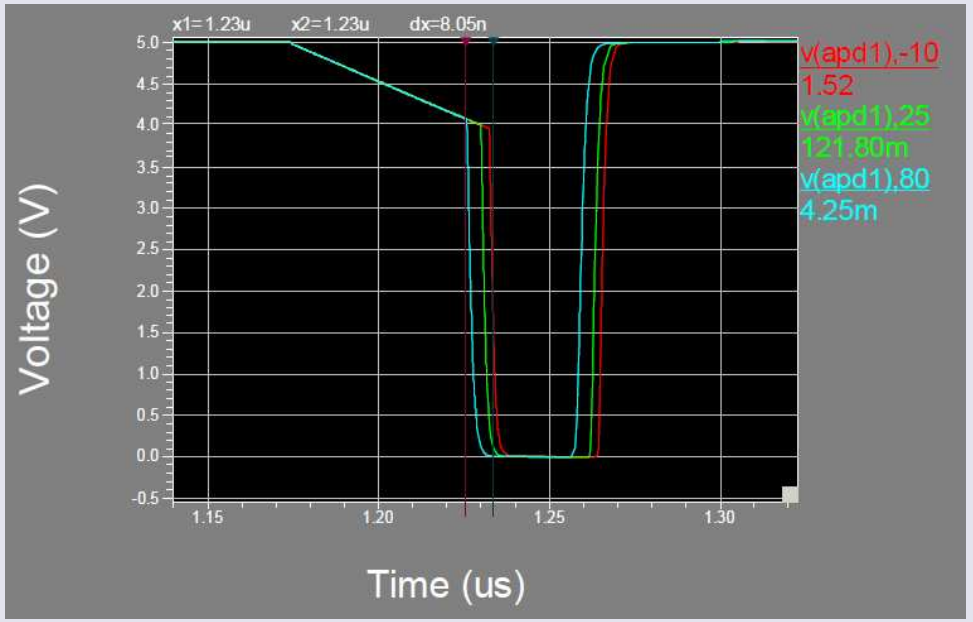
	100MHz Acquisition / 80MHz Readout		
Gate Length (clocks)	Pseudo Random (Hex)	Pseudo Random Binary	Decoded (Hex)
5	**001E**	**000000000011110**	**0005**
6	**003C**	**000000000111100**	**0006**
7	**0078**	**000000001111000**	**0007**
8	**00F0**	**000000011110000**	**0008**
9	**01E1**	**000000111100001**	**0009**
10	**03C3**	**000001111000011**	**000A**
11	**0787**	**000011110000111**	**000B**
12	**0F0F**	**000111100001111**	**000C**
13	**1E1E**	**001111000011110**	**000D**
14	**3C3C**	**011110000111100**	**000E**
15	**7878**	**111100001111000**	**000F**
16	**70F1**	**111000011110001**	**0010**
17	**61E2**	**110000111100010**	**0011**
18	**43C4**	**100001111000100**	**0012**
19	**0788**	**000011110001000**	**0013**

Pixel design, ranging

- **However... Digital counter only is insufficient for ranging**
- **100MHz count rate means 10ns discretization thus a 1.5m accuracy**
- **For better accuracy, an analog interpolator is used.**
- **As the APD fires, an analog voltage is interpolated between two clocks in the pixel memory element.**

Pixel design, ranging

- The goal is to achieve 140ps time resolution
- Is this realistic with respect to temperature?
- Simulation of the APD firing with quenching
- Circuit sensitivity is 90ps /K



➔ **Temperature stabilisation or calibration is mandatory**

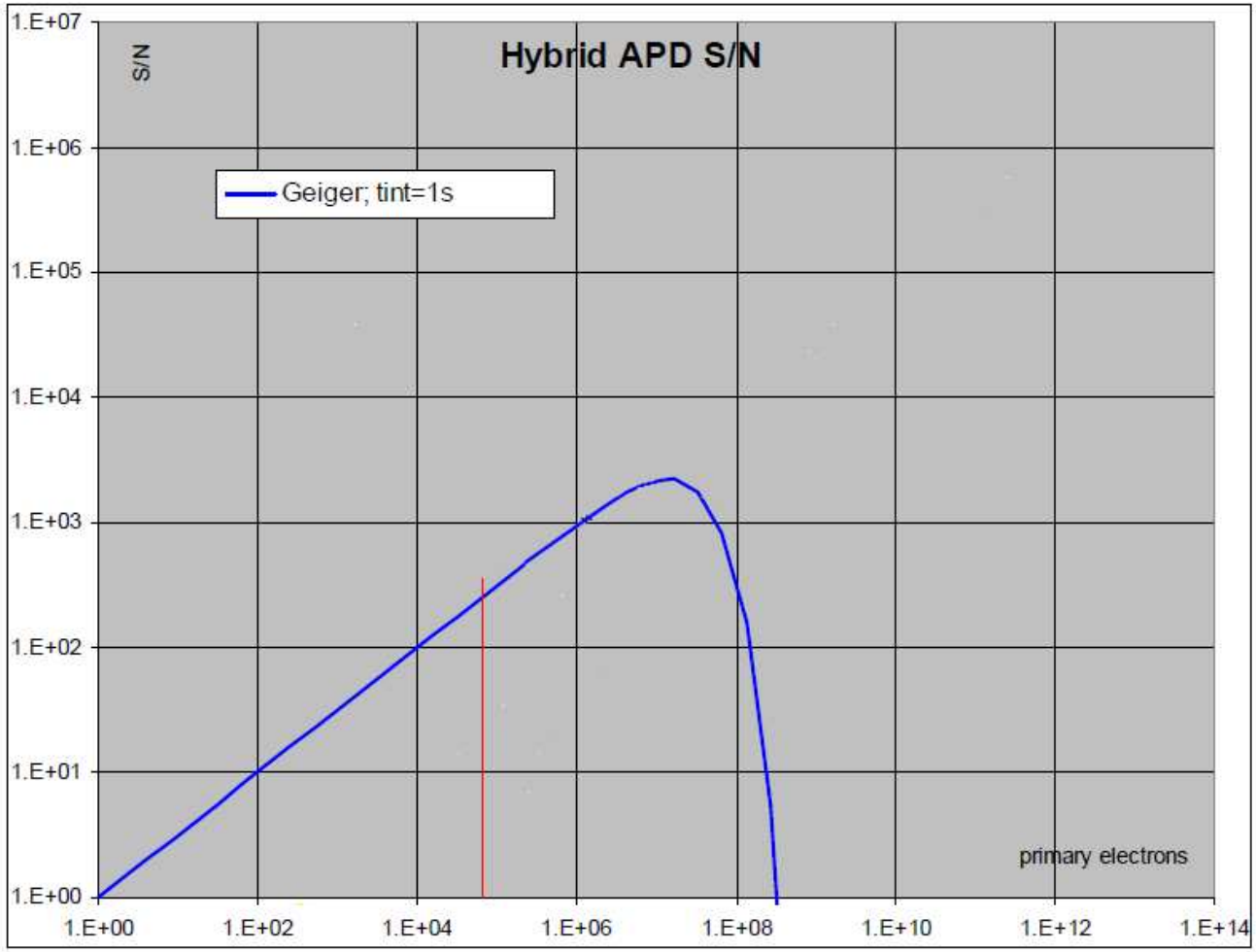
Pixel design, Geiger

- **The sensor is able to do imaging in Geiger counter mode**
- **In Geiger mode, each pixel counts the incoming primary electron.**
- **Ideally:**
  - 1 primary photon = 1 primary electron
  - In counting device, the noise is limited by photon shot noise.

Pixel design, Geiger

- **The sensor is able to do imaging in Geiger counter mode**
- **In Geiger mode, each pixel counts the incoming primary electron.**
- **Ideally:**
  - 1 primary photon = 1 primary electron
  - In counting device, the noise is limited by photon shot noise.
- **However:**
  - The pixel operation (reset, sense, quench.) requires time: 50ns
  - Thus, with a given exposure time, the S/N will roll off at high flux

Pixel design, Geiger



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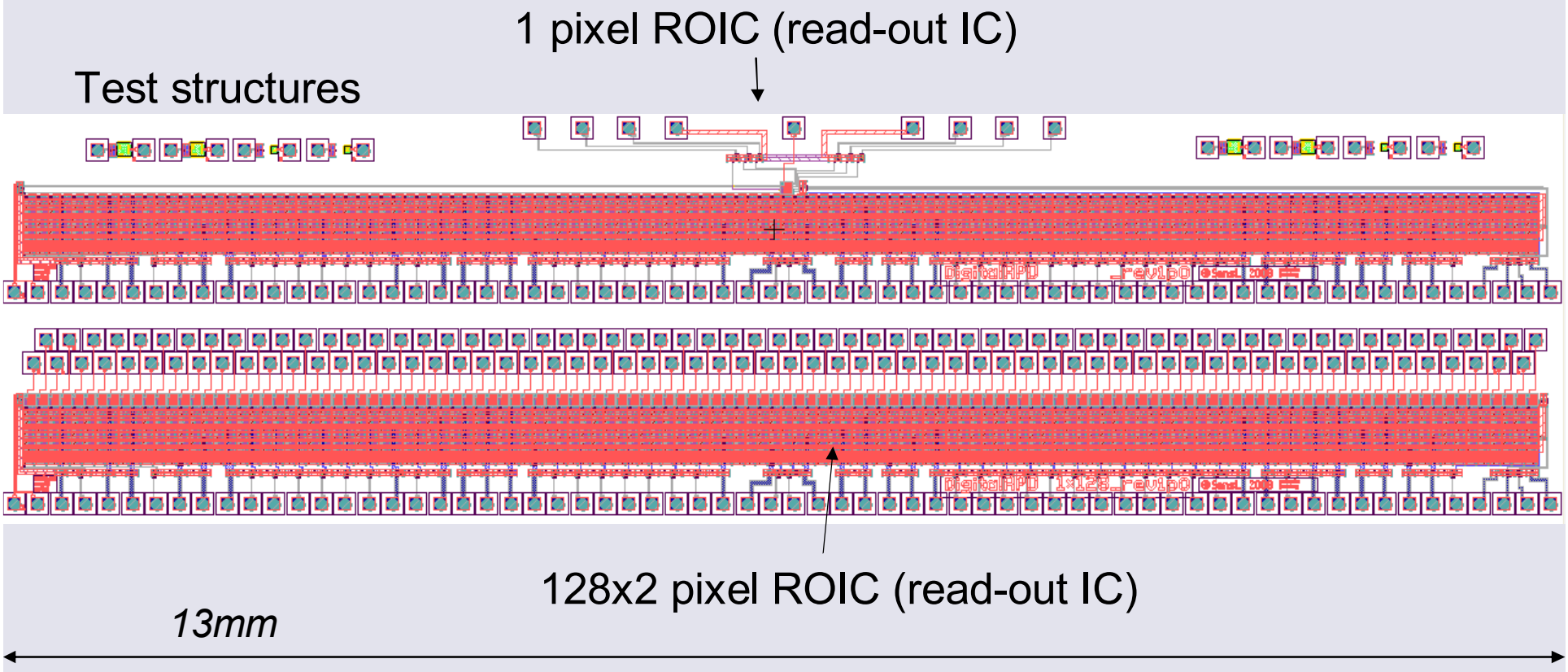
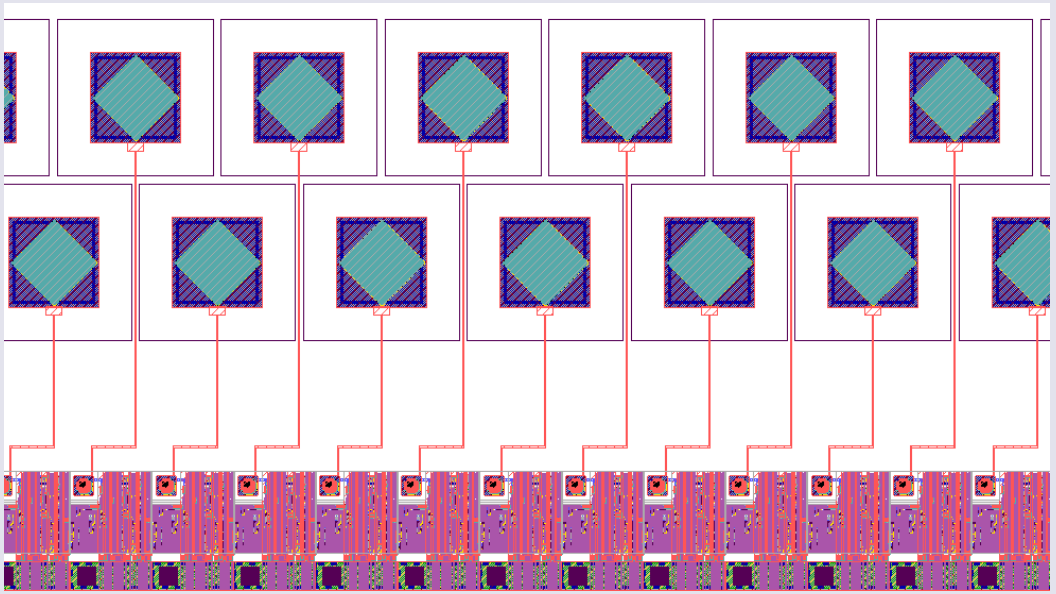
ROIC design

- **The pixel array is scalable.**



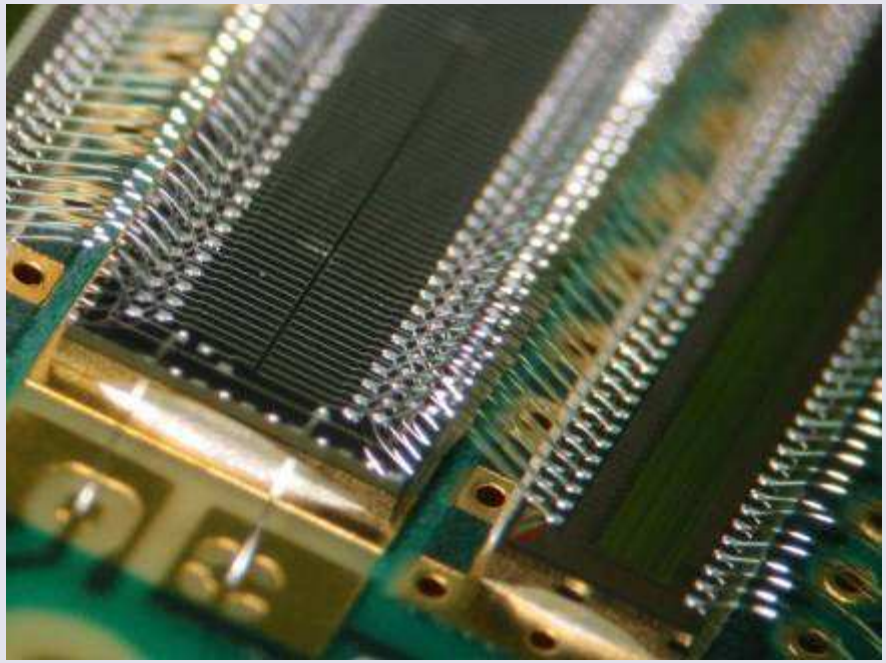
ROIC design

- **The pixel array is scalable**
- **It is designed for lateral wire bonding**
  - One row of 128 pixels
  - Two rows of 128 pixels interleaved



ROIC design

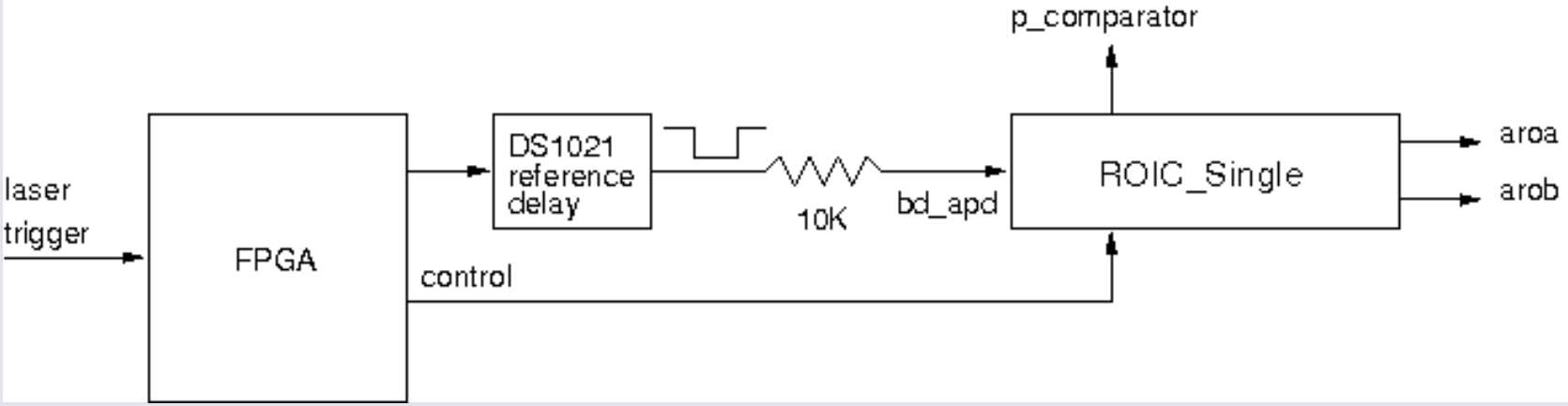
- **The pixel array is scalable**
- **It is designed primarily for lateral wire bonding**
  - One row of 128 pixels
  - Two rows of 128 pixels interleaved
  - 256 bondpads to APDs
  - 136 bondpads to board



ROIC interfacing

DIGITAL

- **differential LVDS output, up to 100MHz**
- **Compatible with DS1021 reference timing generator**
- **Accurately controls the timing of the triggering of the quench circuit**

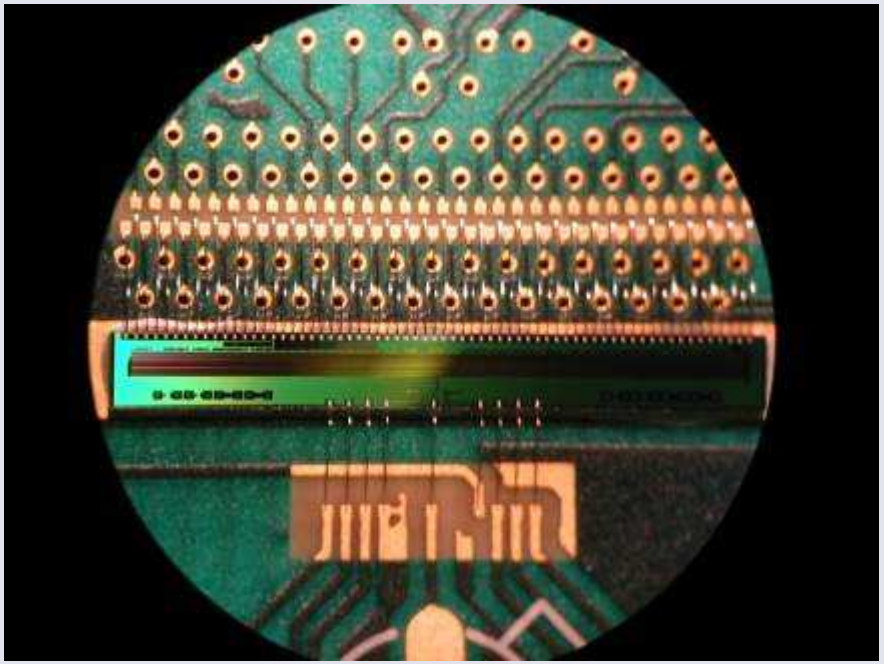


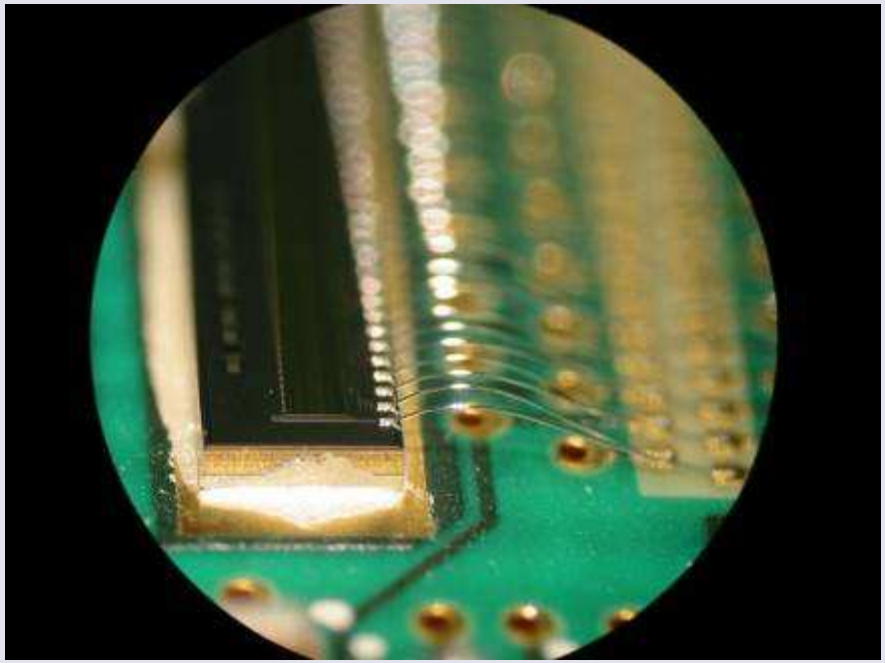
ANALOG

- **Pseudo Differential analog output**
- **15MHz pixel readout rate**

Hybrid assembly

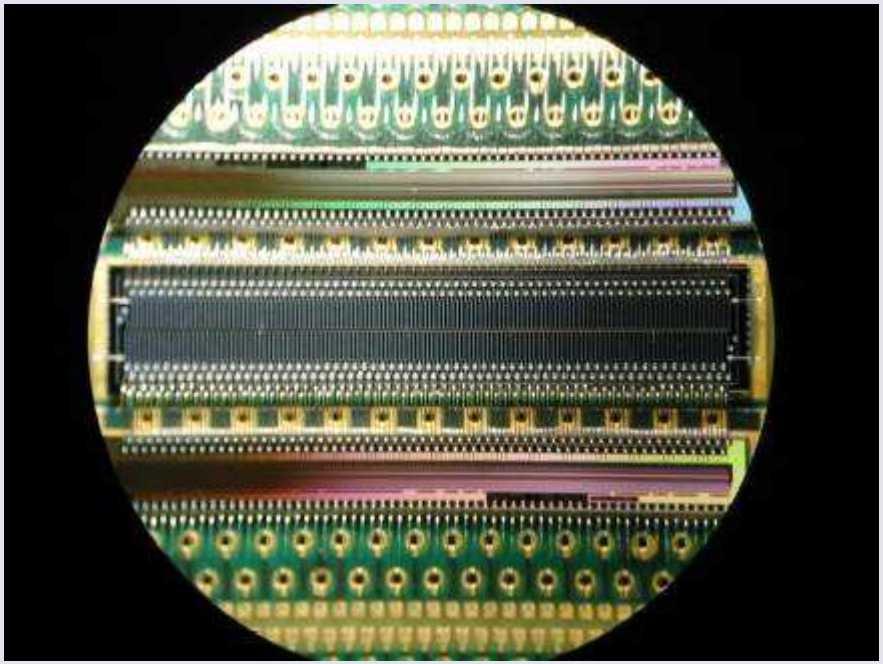
- **Single detector version**
- **73 wirebonds, chip on board**

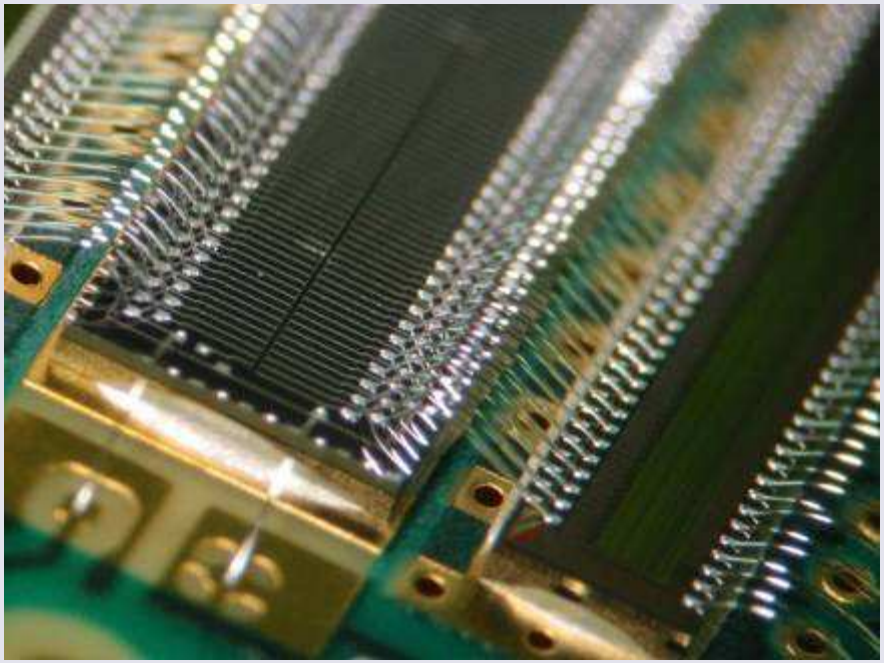




Hybrid assembly

- **2x128 ROIC**
- **256 APD detector array**





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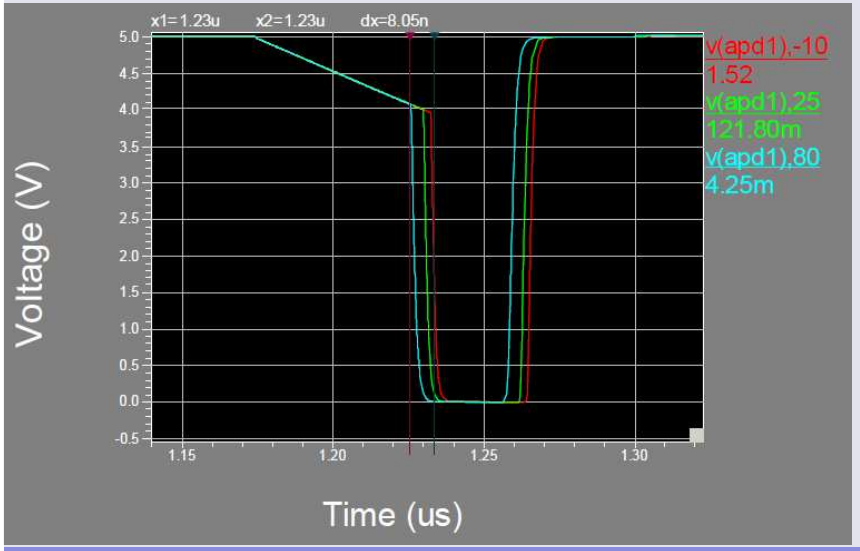
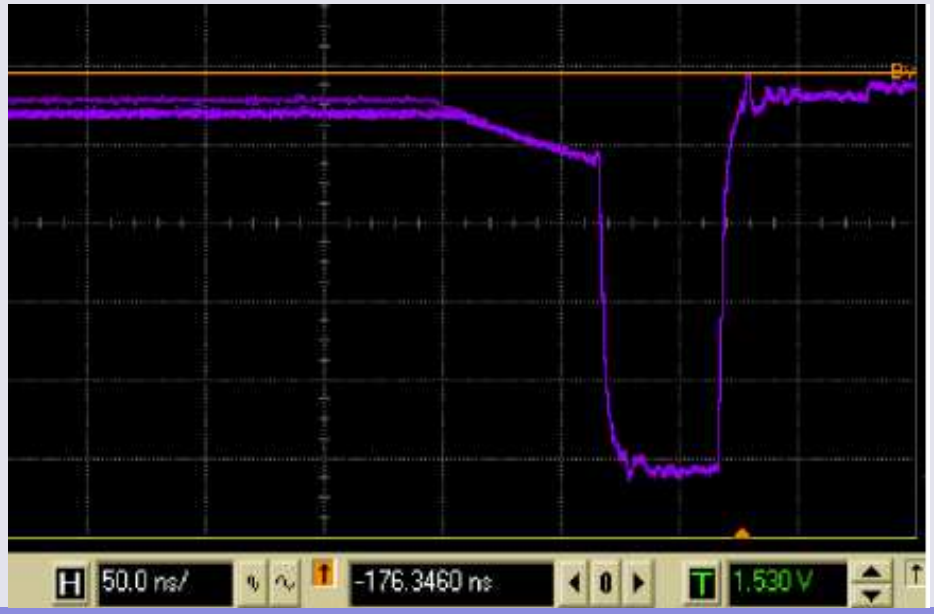
Performance

- **Several chips have been assembled**
  - Single row or dual rows
  - Tested with resistive load first, then discrete photodiodes and APD arrays



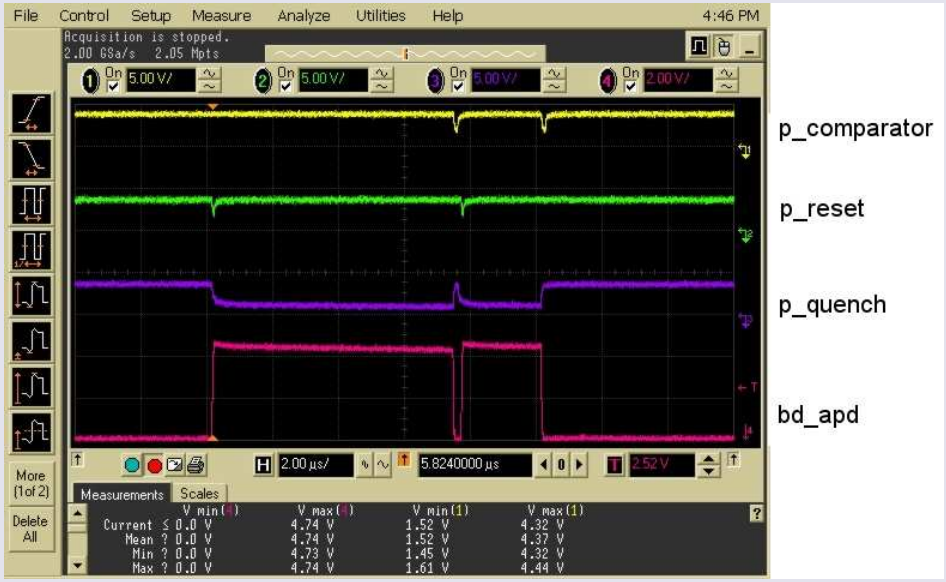


Performance

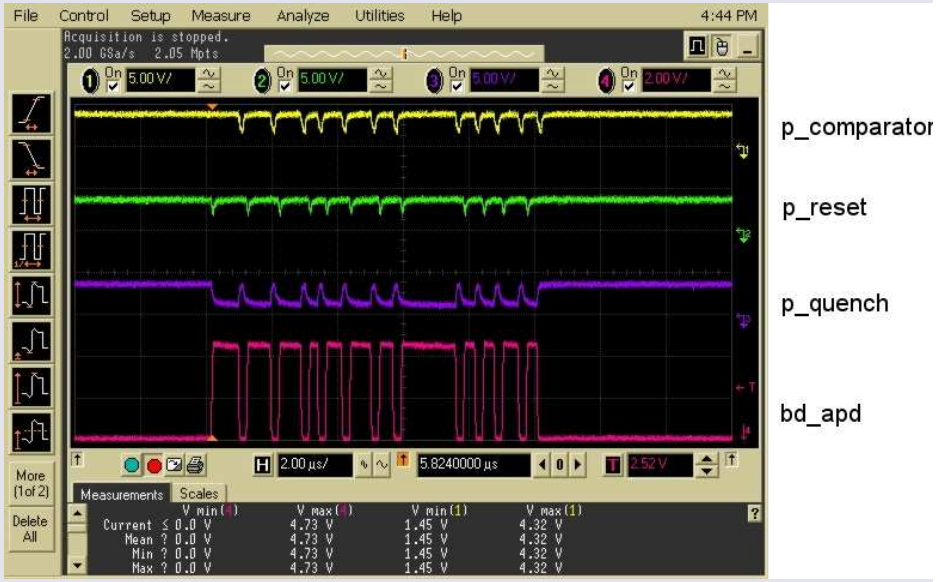
- **Quench, Sense circuit and Reset timing:**

Response of a 50µm APD

Dark condition



illuminated condition

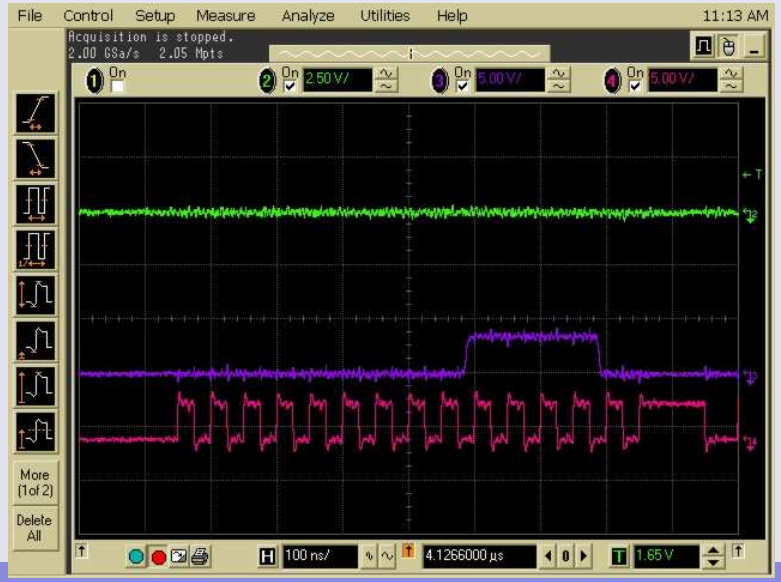


Performance

- **Digital testing:**
  - **Acquisition : 10…100 MHz**
  - **Readout: 10…80 MHz**

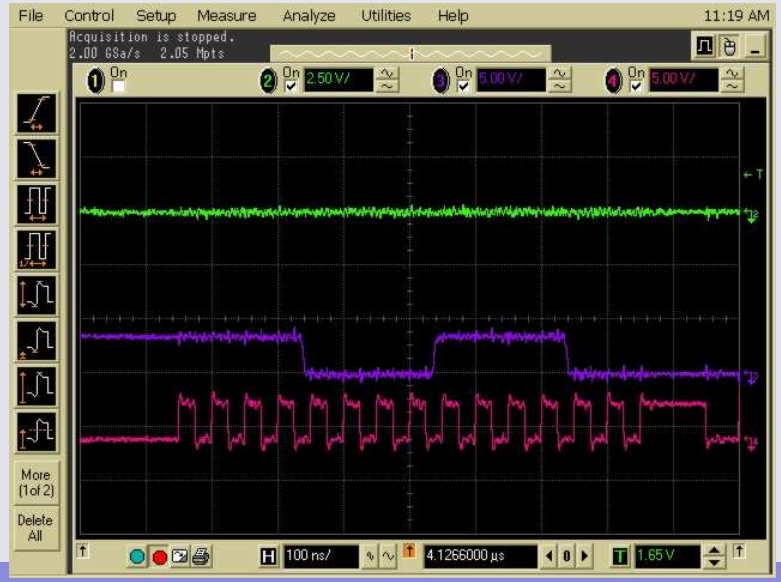
Gate duration 2 clocks

PRC: 003C Decoded:0006



Gate duration 11 clocks

PRC: 7878 Decoded:000F

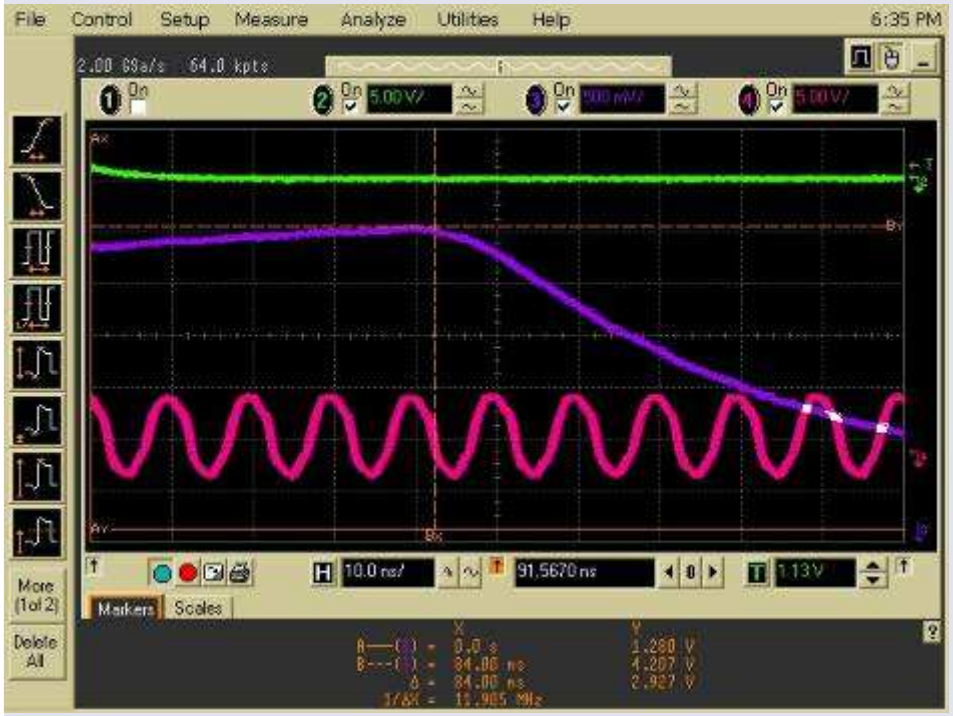


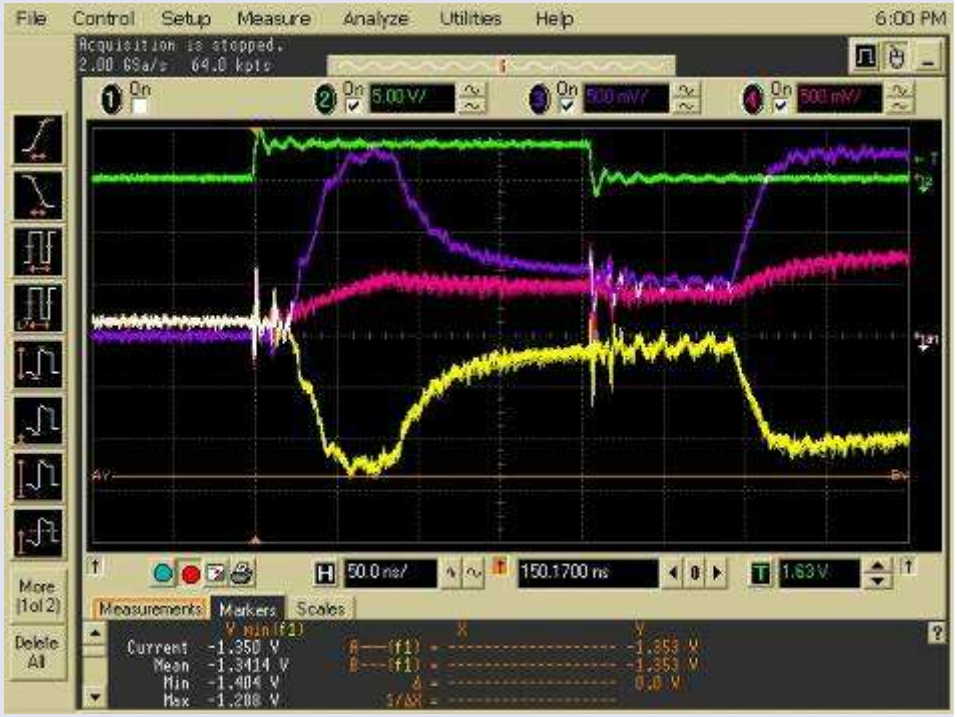
Performance

- **Time of flight testing**
- **Experiment:**
  - ROIC is electrically triggered
  - Trigger is swept with 100ps step over 25ns
  - DIGITAL count is recorded
  - ANALOG interpolated value is recorded

Performance

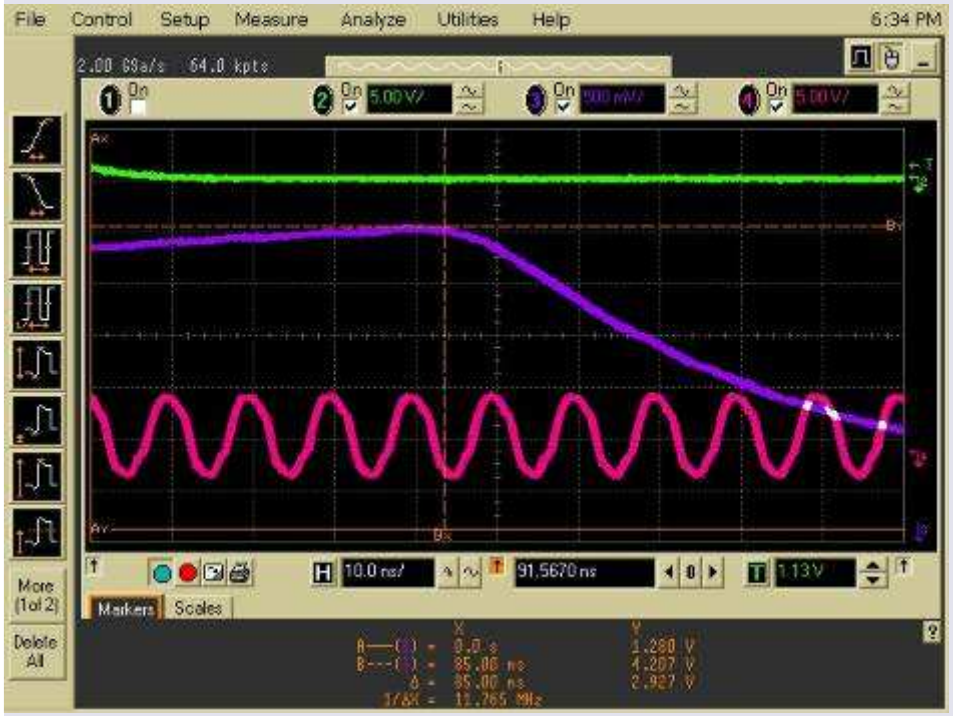
- **ROIC TAC circuit testing @50ns delay**

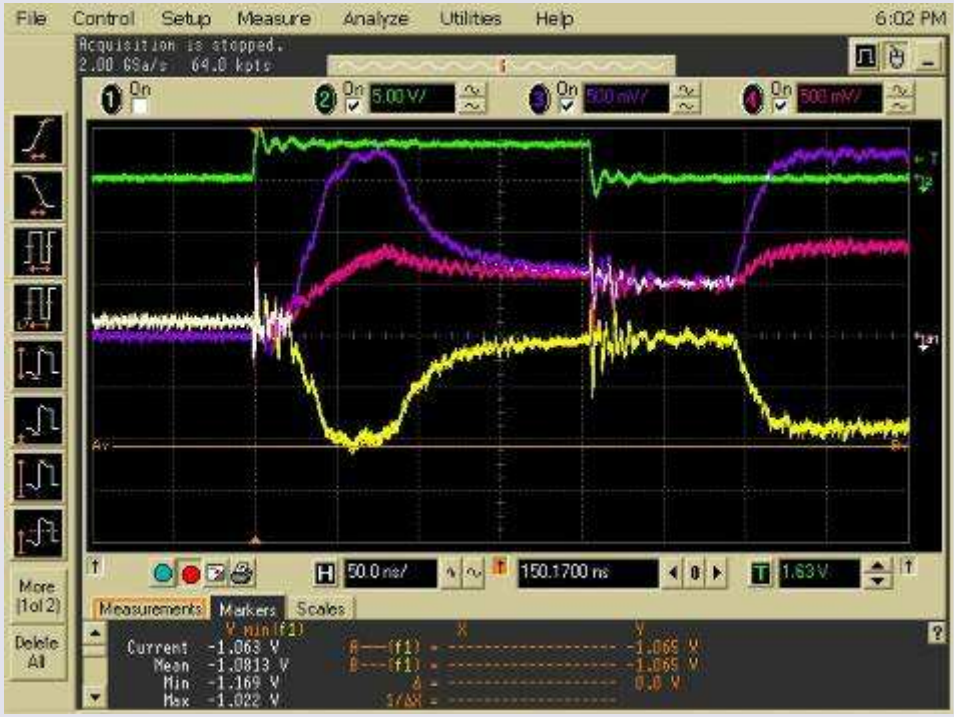




Performance

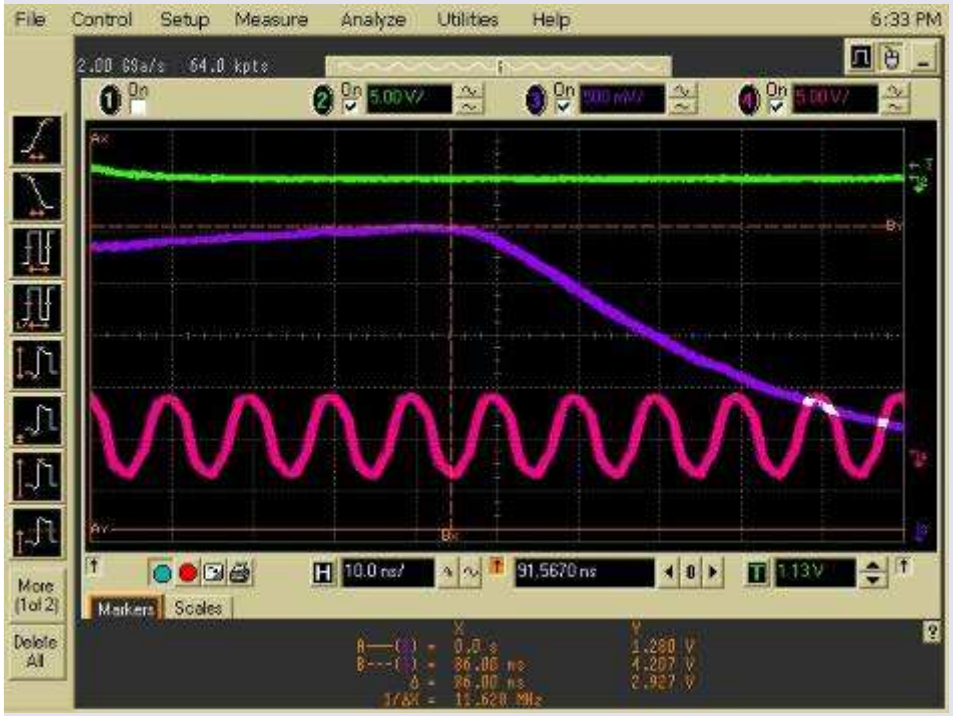
- **ROIC TAC circuit testing @51ns delay**

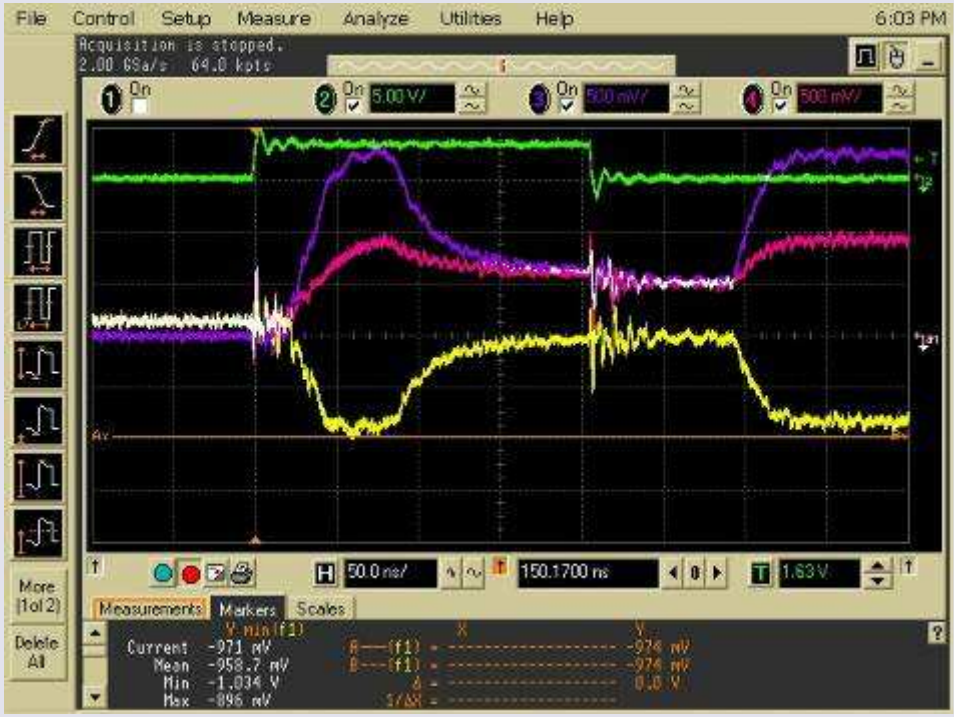




Performance

- **ROIC TAC circuit testing @52ns delay**





Performance

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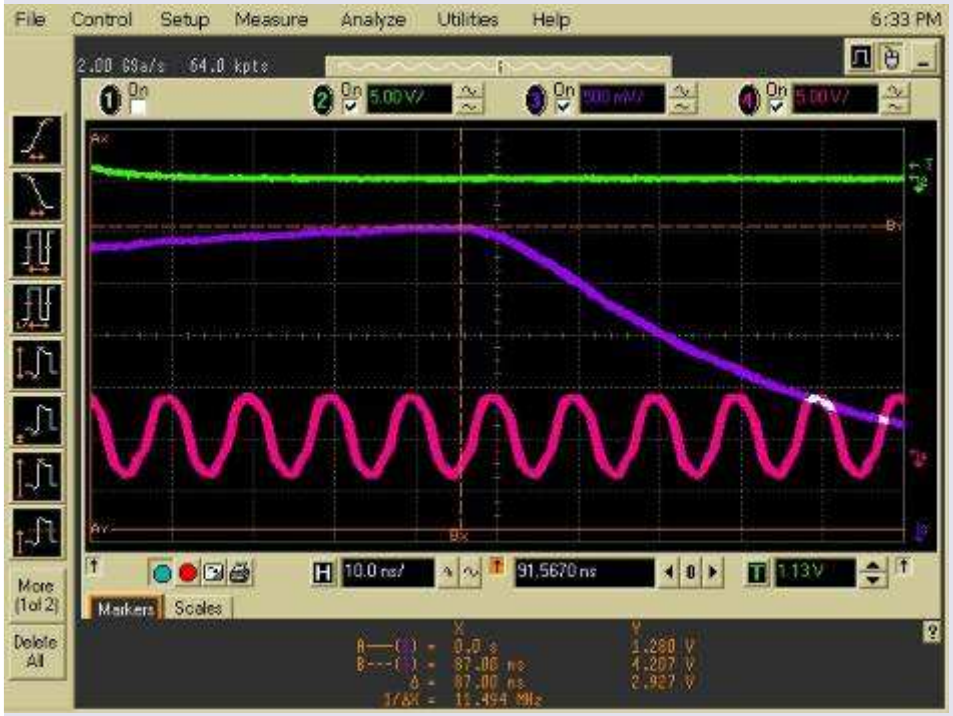
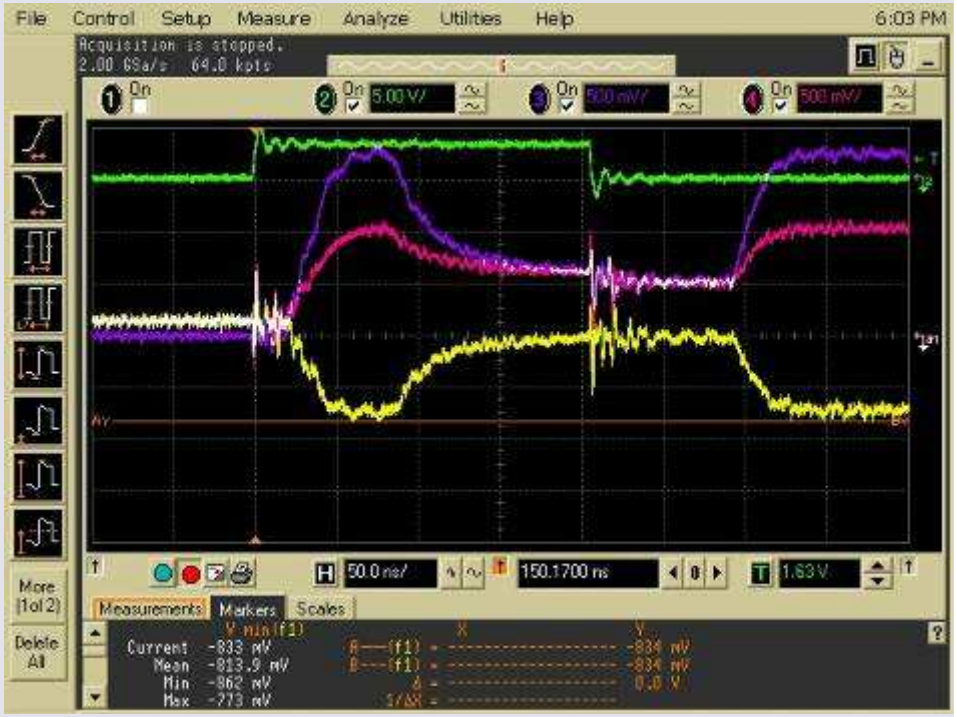
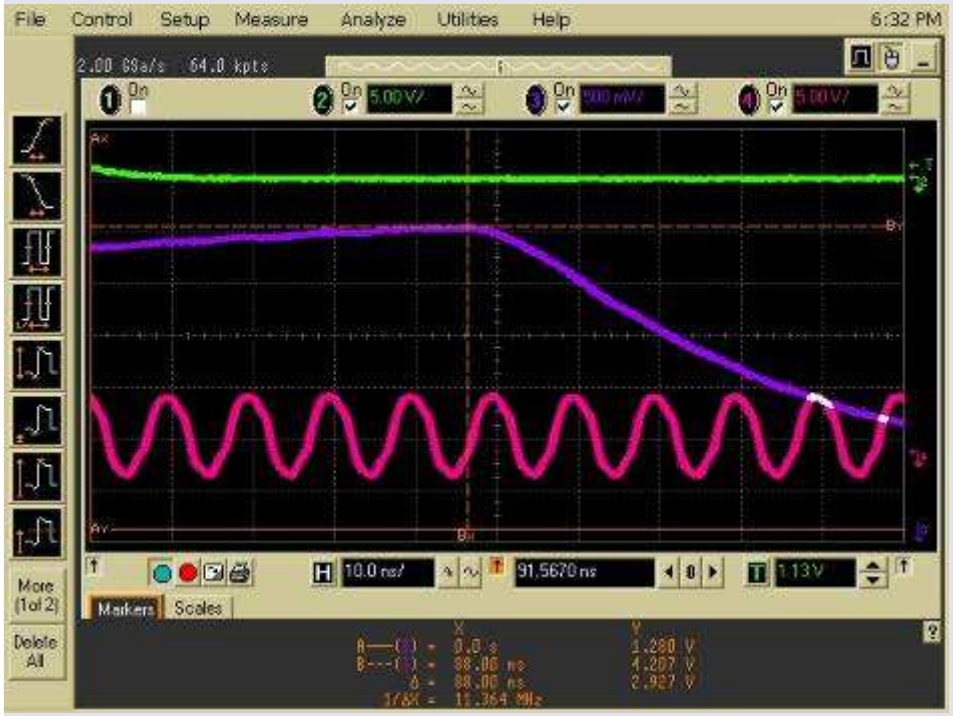
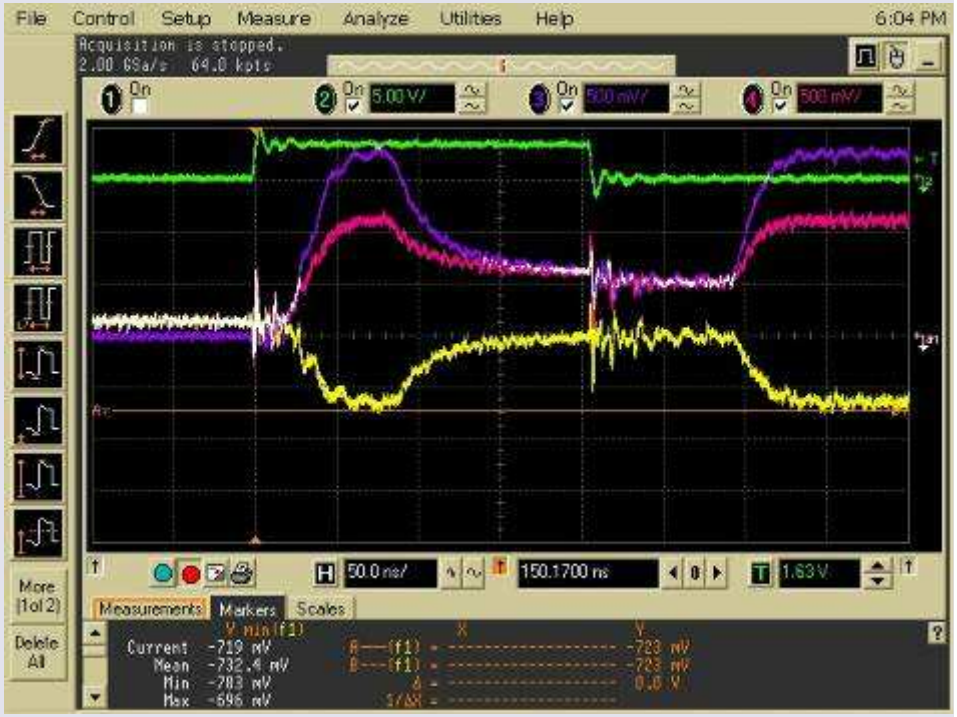




Performance

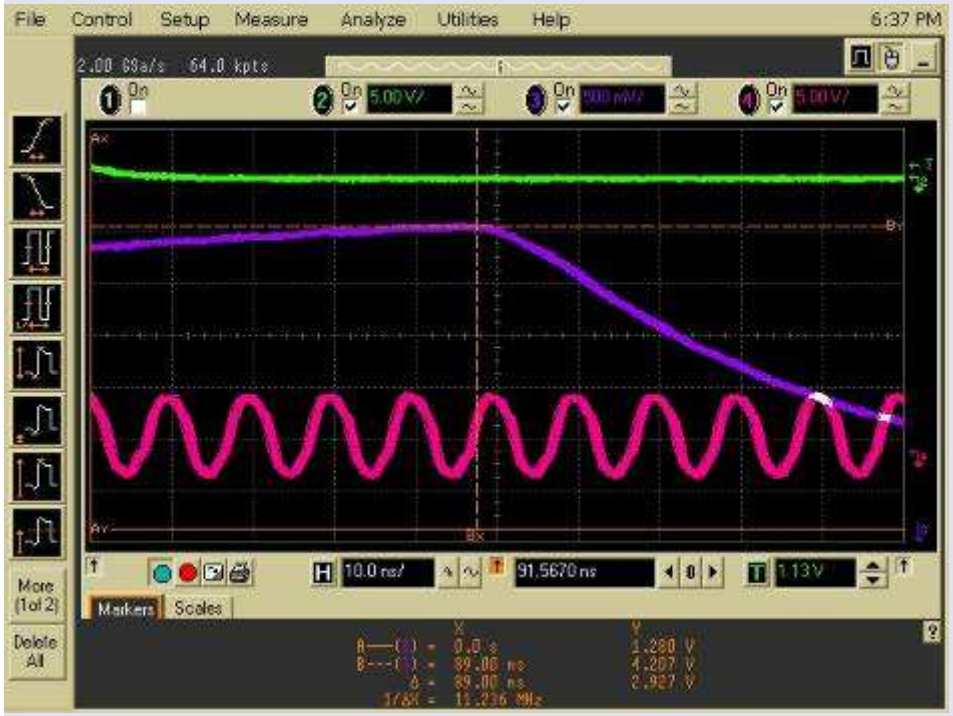
- **ROIC TAC circuit testing @54ns delay**

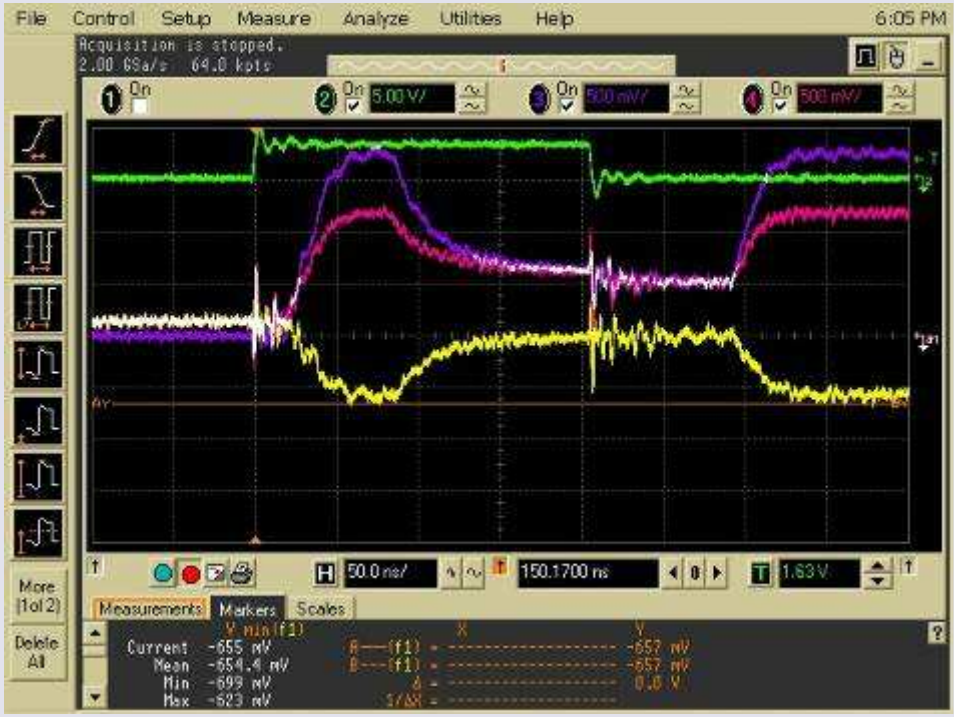




Performance

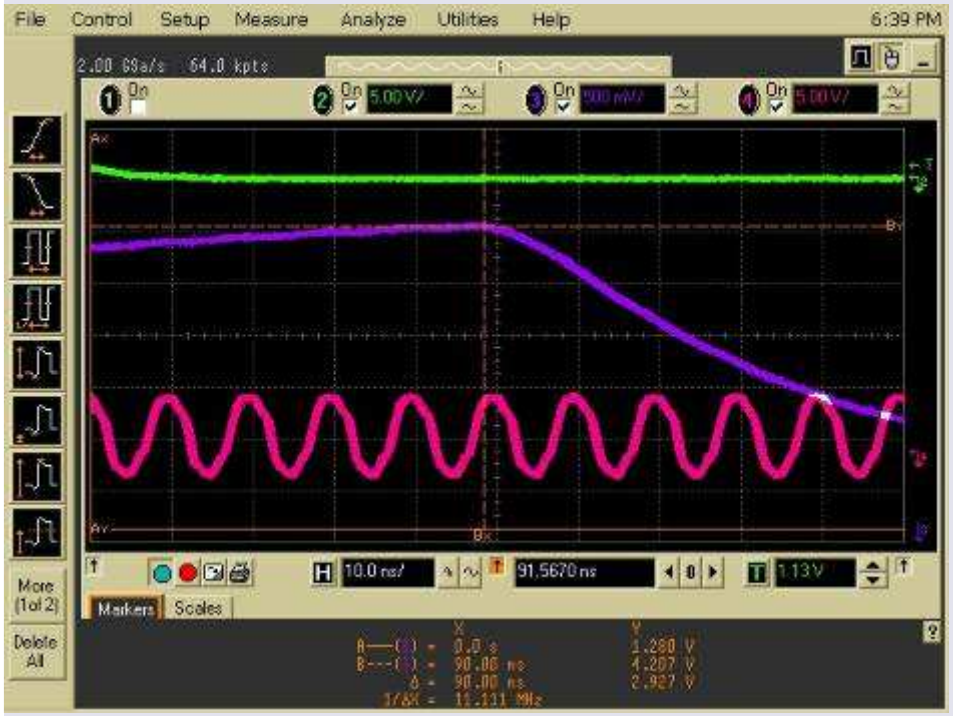
- **ROIC TAC circuit testing @55ns delay**

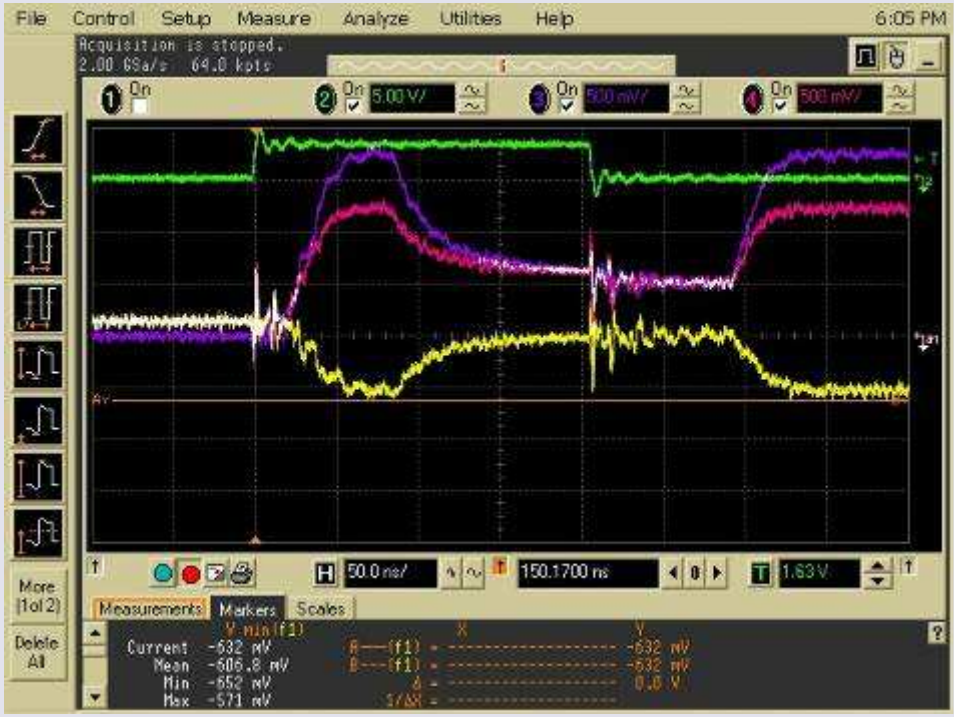




Performance

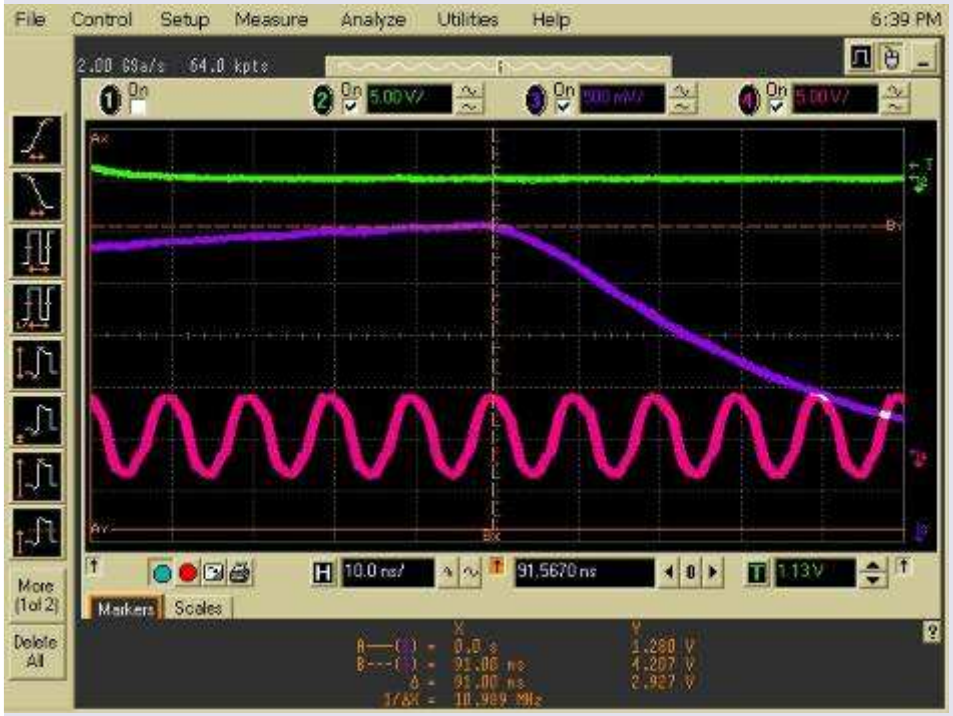
- **ROIC TAC circuit testing @56ns delay**

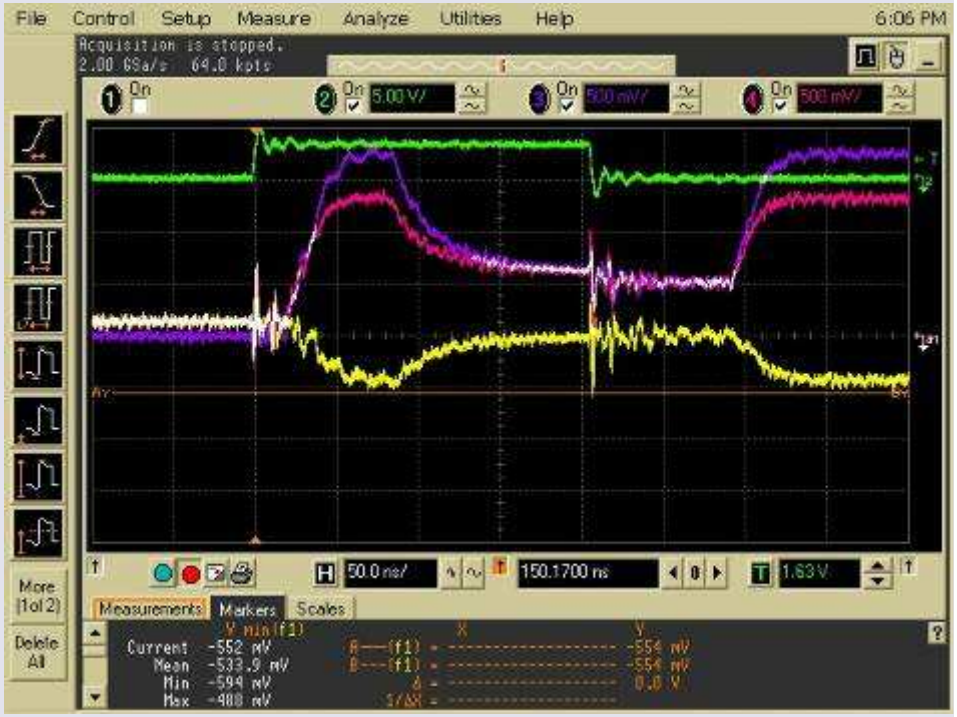




Performance

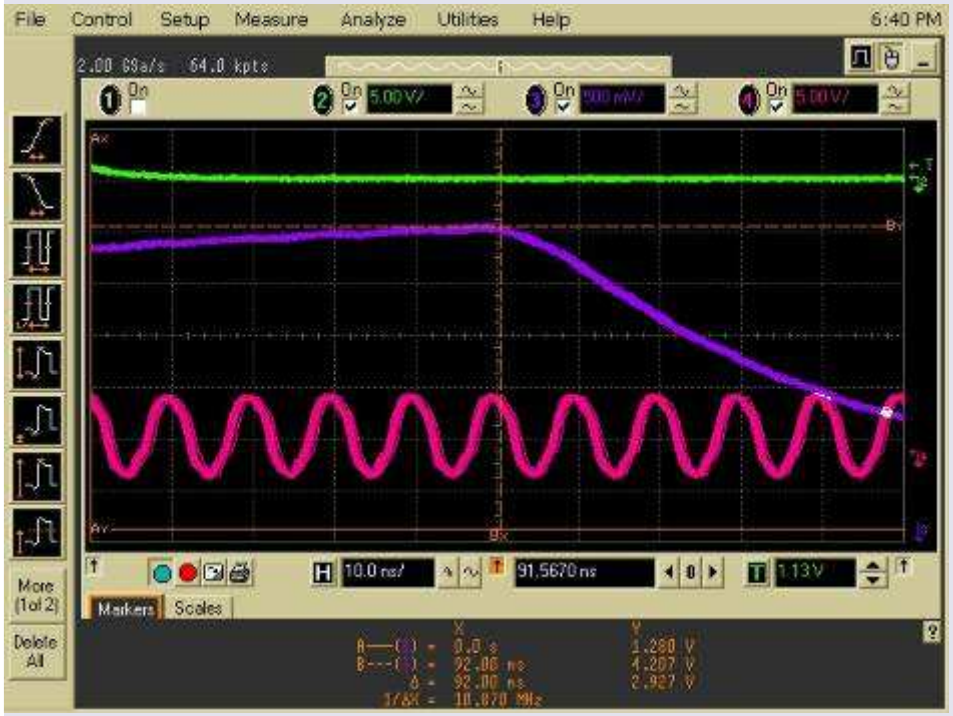
- **ROIC TAC circuit testing @57ns delay**

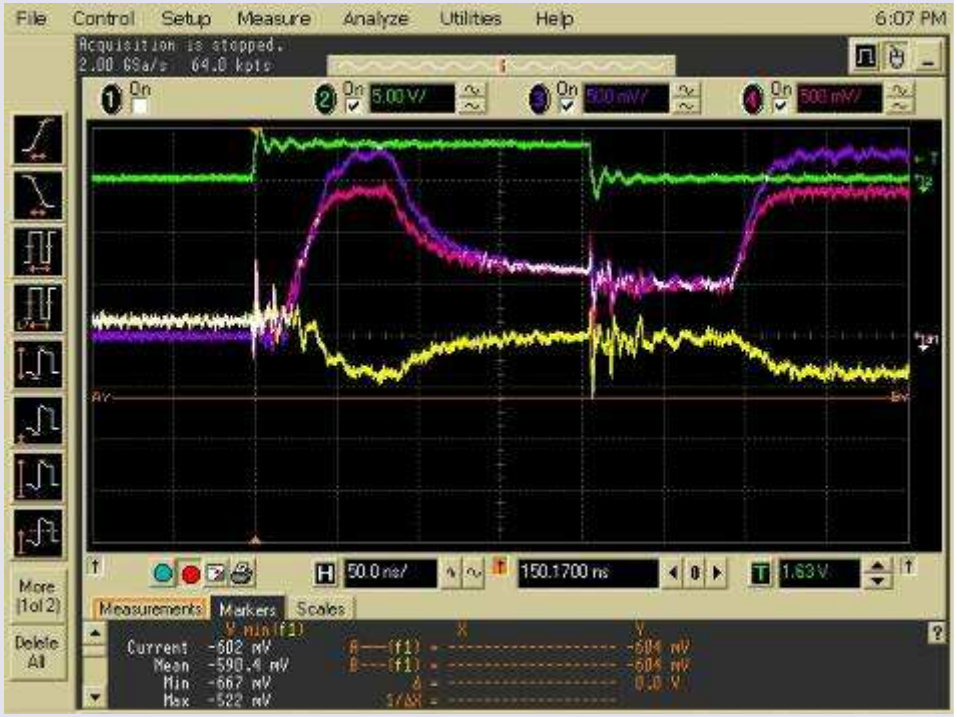




Performance

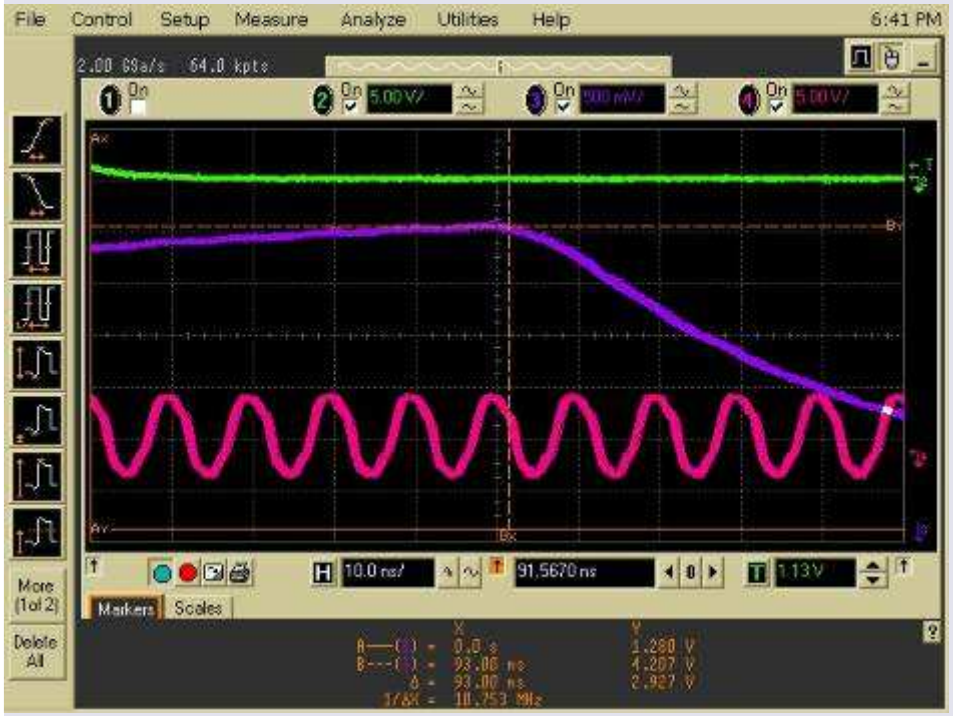
- **ROIC TAC circuit testing @58ns delay**

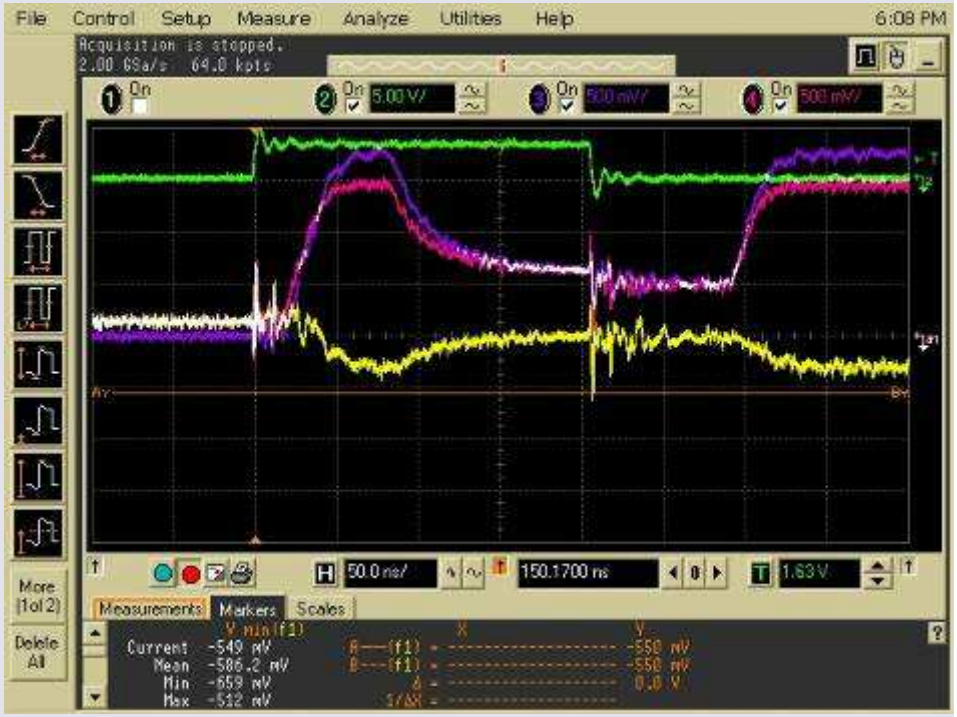




Performance

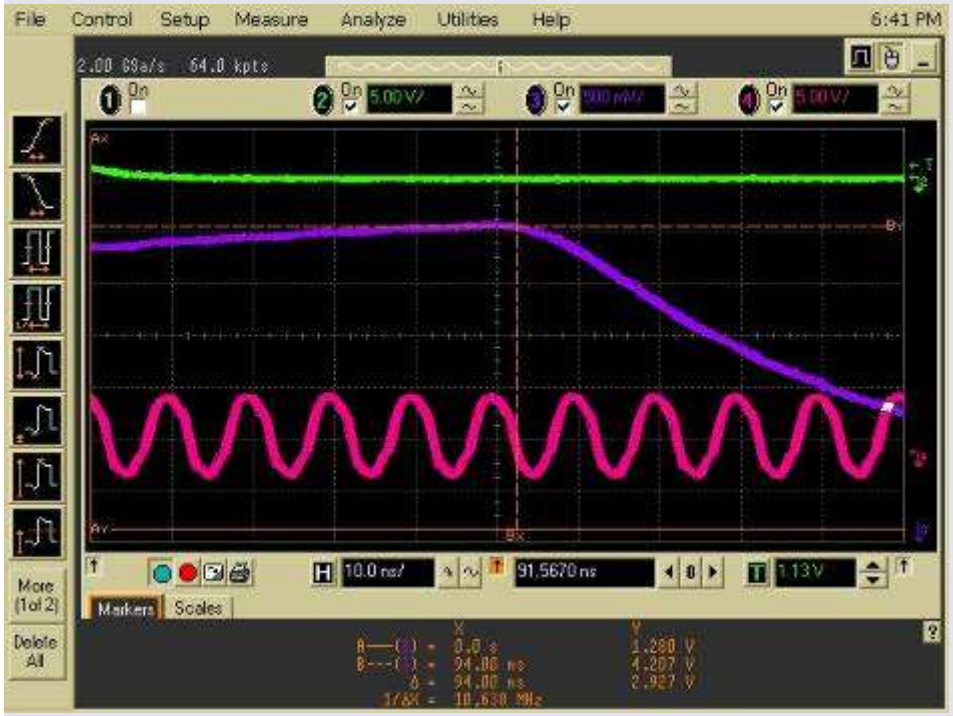
- **ROIC TAC circuit testing @59ns delay**

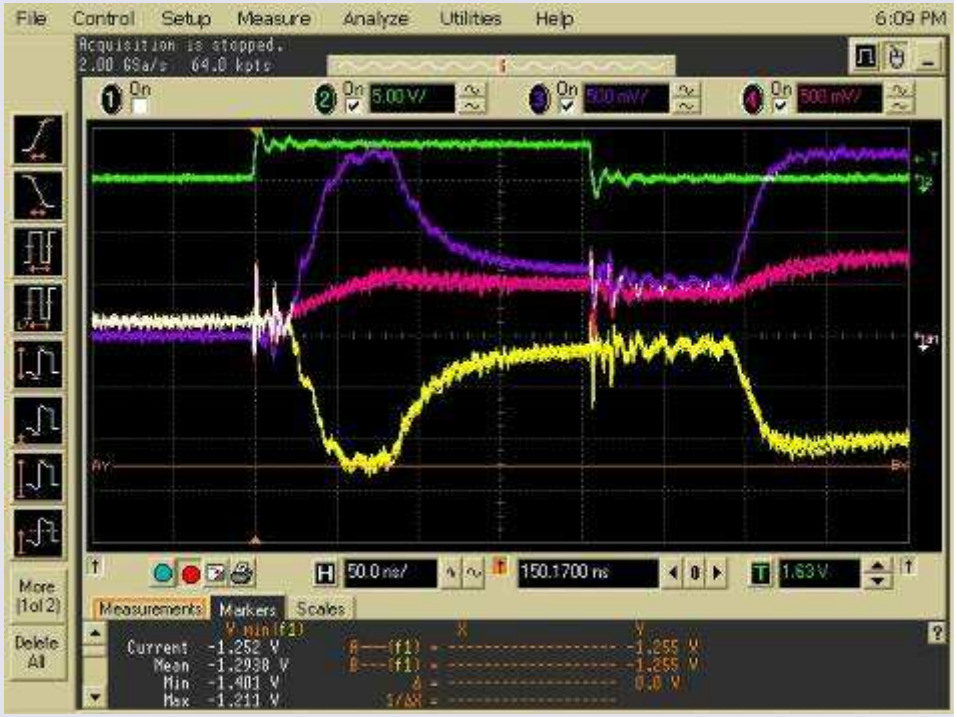




Performance

- **ROIC TAC circuit testing @60ns delay**



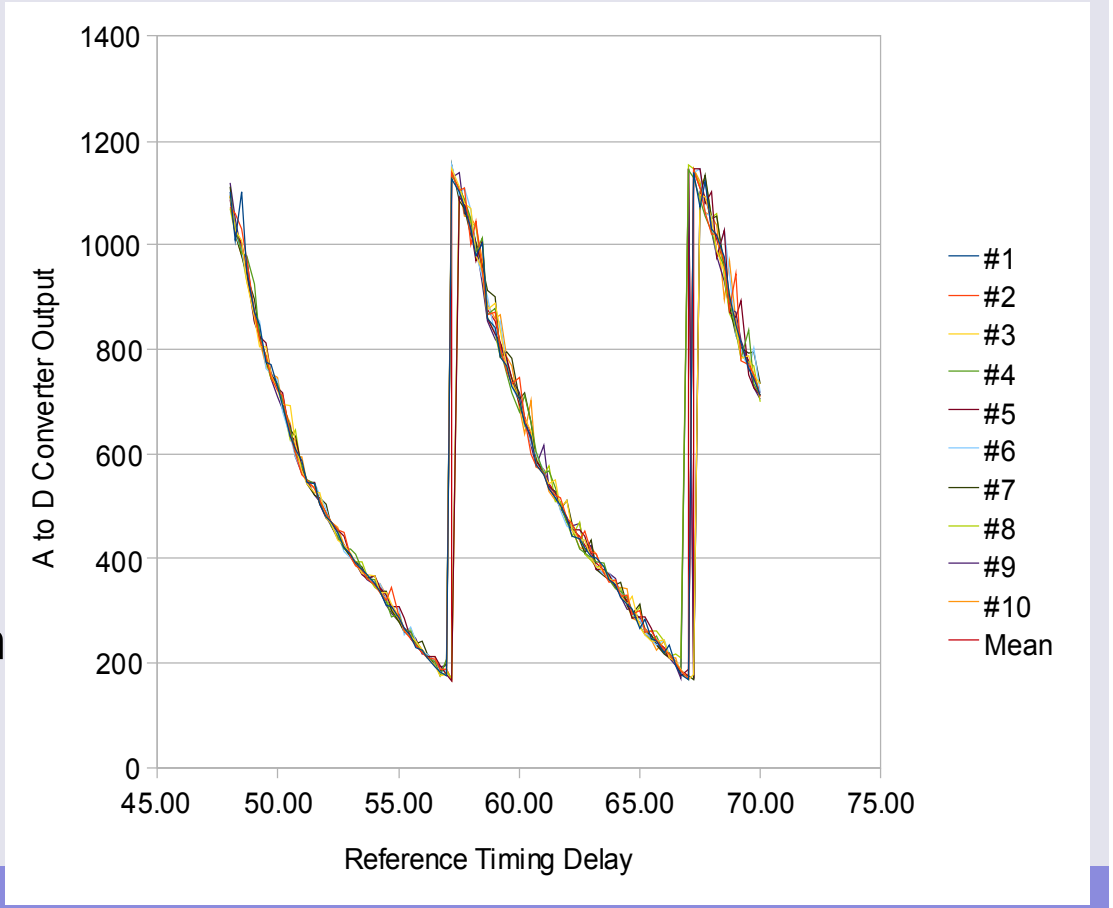


Performance

- **Digitally converted interpolated output**
  - Standard deviation measured 14 LSB_{RMS} average
  - Corresponds to accuracy of 14 x 11ps/lsb = 154ps_{RMS}

➔2cm distance resolution

Over 5000 m dynamic



outline

- SPAD background
- Brief specifations
- Pixel features
- ROIC and detector design
- Performance & Measurements
- **Conclusions and perspectives**

conclusions

- **Conclusion**
  - Sophisticated APD+ROIC pixel with multiple modes of operation
    - Geiger mode (SPAD) counting
    - Distance ranging, digital at 100MHz
    - Analog interpolation of distange ranging
    - 15bit and 7bit counting
  - Hybridization of ADP array and ROIC
  - System built around APD and ROIC
  - We demonstrated a 2cm accuracy ranging with 5.000m dynamic

conclusions

- **Perspective**
  - APD will continue to be tested in *imaging* Geiger mode as well
  - The pixel design is also foreseen to be instantiated in a 2D array, to be studied

Last slide

- **Caeleste and sensL would like to acknowledge their partners:**

ESA (WP7 framework)