MPPC & SPAD
Future of Photon Counting Detectors

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- Single-Photon Avalanche Photodiode (SPAD)
- Silicon Photomultiplier (SiPM)
- Concluding remarks
Introduction
Terminology

PD – Photodiode

APD – Avalanche photodiode

SPAD – Single-photon avalanche photodiode

SPPC – Single-pixel photon counter; another name for SPAD

SiPM – Silicon photomultiplier

MPPC – Multi-pixel photon counter; another name for SiPM

PMT – Photomultiplier tube

The same

The same
Generic PN junction: modes of operation

- $V_{BD}$
- $I$
- $V$

- Geiger region
- Linear mode APD operates in this region
- PD operates in this region

SPAD and SiPM operate in this region.
PN junction devices

- PD (Photodiode): $1\gamma \rightarrow 1$ pair
- APD ( Avalanche Photodiode): $1\gamma \rightarrow \sim 100$ pairs
- SPAD (Single Photon Avalanche Diode): $1\gamma \rightarrow \infty$ pairs
Attributes of a photodiode

1. Detector of choice for sufficiently high input light level
2. Wide spectral coverage (from UV to IR) for a family of photodiodes
3. Inexpensive and easy to use
4. Low intrinsic noise
5. Can be used in arrays and available in modules

Si PDs

InGaAS PDs

PD arrays with amplifier

PD module
Attributes of an avalanche photodiode (linear mode)

1. Detector of choice for light levels too high for a PMT/SiPM but too low for a photodiode
2. Intrinsic gain up to ~100
3. Wide spectral coverage (200 nm – 1700 nm) for a family of avalanche photodiodes
4. Can be used in arrays
5. Available as part of a module

Si APDs

InGaAs APDs

Si APD array

APD module
Single-Photon Avalanche Photodiode (SPAD)
Operation of a SPAD

Without quenching, SPAD operates as a light switch.
Operation of a SPAD (passive quenching)

\[ V_{BIAS} \]
\[ R_Q \]
\[ SPAD \]
\[ R_l \]

\[ R_Q \gg R_l \]

\[ \Delta V = V_{BIAS} - V_{BD} \] (overvoltage)

\[ R_Q \] must be large enough to ensure quenching.
Operation of a SPAD (passive quenching)

\[ \mu = \frac{i_{\text{max}} R Q C J}{e} = \frac{(V_{\text{BIAS}} - V_{BD}) R Q C J}{e(R_Q + R_d)} \approx \frac{(V_{\text{BIAS}} - V_{BD}) C J}{e} = \frac{\Delta V C J}{e} \] (gain)
Operation of a SPAD (passive quenching)

Voltage pulse on $R_S$ due to avalanche

$V_{BIAS}$

$R_Q$

$R_l$

$V_i$

$R_Q \gg R_l$

$\tau \sim R_Q C_f$ (recovery characteristic time)

$10s - 100s of ns$
Photon counting with SPAD

\[ V_{\text{BIAS}} \]

\[ R_Q \]

\[ C \]

\[ v(t) \]

\[ R_t \]

\[ v(t) \]

\[ \text{no light} \]

\[ v(t) \]

\[ \text{dark counts} \]

\[ \text{yes light} \]

\[ v(t) \]

\[ \text{time} \]

\[ \text{time} \]
Photon counting with SPAD

Pulses with a duration much shorter than the recovery time.
Photon counting with SPAD

Pulses with a duration longer than the recovery time.
Photon counting with SPAD

\[ V_{\text{BIAS}} \]

\[ R_Q \]

\[ R_I \]

DC

\[ v(t) \]

\[ v(t) \text{ versus time} \]
Active quenching

Photon detection efficiency is a probability that the incident photon is detected. It is a function of wavelength and overvoltage.

\[ \xi = \xi(\lambda, \Delta V) \]
For a given wavelength, photon detection efficiency increases with overvoltage.
Dark count rate depends on temperature and overvoltage. Typical values at room temperature and recommended overvoltage are $10^s - 100s$ $c/s$, depending on the device design.
After-pulsing

![Diagram showing the difference between normal and after-pulsing behavior of a light-sensitive detector (SPAD).](image)

**Normal**

- Light-sensitive
- Photon
- Full recovery

**With after-pulsing**

- Light-sensitive
- Photon
- Full recovery
Product example by Hamamatsu (C14463-050GD)

Photon counting module with SPAD (SPPC)

Electrical and optical characteristics (Ta=25 °C, λ=600 nm, Vs=±5 V, unless otherwise noted)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Spectral response range</td>
<td>λ</td>
<td></td>
<td>370</td>
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<td></td>
<td>nm</td>
</tr>
<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td></td>
<td>600</td>
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<td>-</td>
<td>nm</td>
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<tr>
<td>Fiber connector*3</td>
<td></td>
<td>FC type</td>
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<td>-</td>
<td></td>
</tr>
<tr>
<td>Chip temperature (setting temperature)</td>
<td>Tchip</td>
<td></td>
<td>-20</td>
<td>-</td>
<td>-</td>
<td>°C</td>
</tr>
<tr>
<td>Photon detection efficiency</td>
<td>PDE</td>
<td></td>
<td>25</td>
<td>35</td>
<td>-</td>
<td>%</td>
</tr>
<tr>
<td>Dark count</td>
<td>CD</td>
<td></td>
<td>20</td>
<td>60</td>
<td>-</td>
<td>cps</td>
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<tr>
<td>Afterpulse probability</td>
<td></td>
<td></td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>%</td>
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<tr>
<td>Comparator output</td>
<td></td>
<td>TTL compatible</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td>Current consumption</td>
<td>+5 V</td>
<td>Ic</td>
<td>+200</td>
<td>+1000</td>
<td>-</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td>-5 V</td>
<td></td>
<td>-20</td>
<td>-40</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*3: Recommended fiber: GI 50/125 multimode fiber

Photon detection efficiency [%]

No. of detected photons [c/s]

No. of incident photons [c/s]

Photon detection efficiency [%]

wavelength [nm]

Linearity
Each element of the array (pixel) has its own quenching circuitry (passive or active).
Each element of the array (pixel) has its own quenching circuitry (passive or active).
### SPPC Array Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
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<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
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<tr>
<td>Pixel pitch</td>
<td></td>
<td></td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>µm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td></td>
<td></td>
<td>-</td>
<td>32 × 32</td>
<td>-</td>
<td>Ch</td>
</tr>
<tr>
<td>Diameter and shapes</td>
<td></td>
<td>Octagonal</td>
<td>-</td>
<td>75 × 75</td>
<td>-</td>
<td>µm</td>
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<tr>
<td>Geometrical fill-factor</td>
<td>FF</td>
<td></td>
<td>-</td>
<td>61</td>
<td>-</td>
<td>%</td>
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<tr>
<td>Peak sensitive wavelength</td>
<td>( \lambda_p )</td>
<td></td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>nm</td>
</tr>
<tr>
<td>Spectral response region</td>
<td>( \lambda )</td>
<td>25°C</td>
<td>380</td>
<td>900</td>
<td>-</td>
<td>nm</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>( V_{BR} )</td>
<td>25°C</td>
<td>50</td>
<td>52</td>
<td>54</td>
<td>V</td>
</tr>
<tr>
<td>Temperature coefficient of ( V_{BR} )</td>
<td>( \Delta T_{VBR} )</td>
<td>-20 ~ +30°C</td>
<td>56</td>
<td>-</td>
<td>mV/°C</td>
<td></td>
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<tr>
<td>Gain</td>
<td>M</td>
<td></td>
<td>1 × 10^6</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Photon detection efficiency</td>
<td>PDE</td>
<td>470 nm</td>
<td>30</td>
<td>-</td>
<td>%</td>
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<td></td>
<td></td>
<td>525 nm</td>
<td>30</td>
<td>-</td>
<td>%</td>
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<tr>
<td></td>
<td></td>
<td>630 nm</td>
<td>20</td>
<td>-</td>
<td>%</td>
<td></td>
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<tr>
<td>Dark count rate</td>
<td>DCR</td>
<td>35°C, ( V_c = 2.0 ) V</td>
<td>20k</td>
<td>-</td>
<td>Hz</td>
<td></td>
</tr>
<tr>
<td>Cross talk probability</td>
<td>CT</td>
<td>35°C, ( V_c = 2.0 ) V</td>
<td>75</td>
<td>-</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Afterpulse probability</td>
<td>AP</td>
<td>50 ns hold-off</td>
<td>3</td>
<td>-</td>
<td>%</td>
<td></td>
</tr>
</tbody>
</table>
Comments on SPAD arrays

1. The array can be customized to specific user’s needs.
2. Hamamatsu is working on improving crosstalk.
3. Hamamatsu is working on higher resolution array (smaller pixels).
4. Hamamatsu is working on IR version of the array.
5. Hamamatsu will work with users on developing customized ASICs
6. Demos are available for evaluation.
Importance of ASIC (example)

Measuring distance with a SPAD

\[ t = 0 \]

\[ t = T \]

Pulse emission

\[ \Delta t = \frac{2d}{c} \]

laser

timer

SPAD

target
Importance of ASIC (example)

1. Multiple pulse illumination provides distance information to the target. The information comes from a histogram of trigger times.

2. An ASIC producing such histogram (per pixel) is part of the sensor.
Silicon Photomultiplier (SiPM)
Naming conventions

SiPM – Silicon Photomultiplier
MPPC – Multi-Pixel Photon Counter

SSPM – Solid-State Photomultiplier
PMAD – Multi-Pixel Avalanche Photodiode
G-APD – Geiger Mode Avalanche Photodiode
MPGM APDs – Multi-Pixel Geiger-Mode Avalanche Photodiodes

Most-commonly-used names
Structure

SiPM is an array of microcells

Also known as multi-pixel photon counter (MPPC)
All of the microcells are connected in parallel.
Example of models

S13360-3050DG
metal can, TE cooled, 3 × 3 mm², 3,600, 50 × 50 μm²

S13360-1325CS
ceramic, 1.3 × 1.3 mm², 2,668, 25 × 25 μm²

S13360-1375PE
surface mount, 1.3 × 1.3 mm², 285, 75 × 75 μm²

S13360-6050VE
surface mount, 6 × 6 mm², 14,555, 50 × 50 μm²

DG – metal can
CS – ceramic
PE – surface mount
VE – 4-side buttable (best for arrays)
Operation

\[ V_{BIAS} > V_{BD} \]

Time series: \( v_1 \) and \( v_2 \)

\[ h\nu \]

Currents: \( i_1 \) and \( i_2 \)

Resistance: \( R_t \)
Anatomy of a pulse

- The $RC$ time constant of the slow component depends on microcell size (all else being equal).
- The recovery time $t_r \approx 5 \times$ the $RC$ time constant.
- $t_r$ is on the order of 10s to 100s of ns but in practical situations it is also a function of the detection bandwidth.
Crosstalk

Primary discharge can trigger a secondary discharge in neighboring microcells. This is crosstalk.

Crosstalk probability depends on overvoltage.

2 p.e. crosstalk event
Temperature compensation

\[ V_{BD}(T) = V_{BD}(T_0) + \beta (T - T_0) \]

(breakdown voltage depends on temperature)

The role of the control unit is to adjust \( V_{BIAS} \) so that the overvoltage \( \Delta V \) remains constant (and thus gain) as temperature changes.
Product example by Hamamatsu (S13360, 50 μm pitch)
Linearity and dynamic range ($\delta$ illumination)

In the limit of $\delta$ –illumination, dynamic range and linearity depend on the number of microcells.

$$N_f = N_t \left(1 - e^{-N_\gamma \cdot PDE/N_t}\right)$$

- $N_t$ – Number of microcells
- $N_f$ – Average number of fired $\mu$-cells
- $N_\gamma$ – Number of photons in a pulse

The diagram shows a plot of $N_f$ vs. number of potentially detectable photons, with solid lines fitting to the equation. The curves are labeled with different microcell configurations: 4 ch of SiPM array (56,700 pixels) and 1 ch of SiPM array (14,400 pixels).
Linearity and dynamic range (finite-pulse illumination)

For a given number of photons in a pulse, the number of effective fired microcells increases with the pulse duration.

\[ N_f = N_t \left( \frac{T_p}{t_r} \right) \left( 1 - \exp \left( -N \gamma \cdot PDE \right) \right) \]

- \( T_p \) – Pulse duration
- \( t_r \) – Recovery time

3,600 microcells
3 × 3 mm²

From Grodzicka et al. 2015
For some SiPMs Hamamatsu provides a linearity plot for DC illumination. This plot can be transcribed from $\lambda = 850 \text{ nm}$ to any other wavelength.
Modes of operation

incident light level

(photons)

(analog)

(time)
Analog

\[ i_{ph} = e\mu(1 + P_{ct}) \frac{PDE \cdot P \cdot \lambda}{hc} \]

\[ S \frac{N}{i_{ph}R_f} = \sqrt{i_{SS}^2R_f^2 + i_{DS}^2R_f^2 + \frac{4kT\Delta f}{R_f}R_f^2} \]

\[ i_{SS}^2 = 2ei_{ph}\mu F\Delta f \quad \text{(signal photon shot noise)} \]

\[ i_{DS}^2 = 2ei_{D}\mu F\Delta f \quad \text{(dark current shot noise)} \]

\[ i_J^2 = \frac{4kT\Delta f}{R_f} \quad \text{(Johnson noise of the feedback resistor)} \]
Photon counting

SiPM → preamplifier → amplifier → discriminator → pulse shaper → counter

ULD

LLD

Time
Photon counting

\[
\frac{S}{N} = \frac{n_S \sqrt{T_{\text{exp}}}}{\sqrt{n_S + 2(n_B + n_D)}}
\]

\(T_{\text{exp}}\) – measurement time

\(n_S = n_{\text{tot}} - (n_B + n_D)\)

\(n_{\text{tot}}\) – number of counts per unit time due to “science” light, background light, and dark counts

\(n_B\) – number of counts per unit time due to background light

\(n_D\) – number of counts per unit time due to dark current

All rates are measured with the same exposure time \(T_{\text{exp}}\)
Minimum detection limit (MDL) can be lowered by cooling and limiting the detection bandwidth.
SiPM imaging array, product example by Hamamatsu

S15013-0125NP-01

2D MPPC photon counting image sensor

This array can be used for imaging and for ToF distance measurement (e.g., in flash LiDAR).
SiPM imaging array, product example by Hamamatsu

### Structure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
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<td>MPPC type</td>
<td>-</td>
<td>Equivalent to Si4420</td>
<td>series</td>
</tr>
<tr>
<td>Number of channels</td>
<td>-</td>
<td>32 x 32</td>
<td>ch</td>
</tr>
<tr>
<td>Effective photosensitive area / channel</td>
<td>-</td>
<td>100 x 100</td>
<td>μm</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>-</td>
<td>25</td>
<td>μm</td>
</tr>
<tr>
<td>Number of pixels / channel</td>
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<td>Fill factor</td>
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<td>36.4</td>
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<td>Package type</td>
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<td>Connector</td>
<td>-</td>
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<tr>
<td>Window</td>
<td>-</td>
<td>Borosilicate glass</td>
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<tr>
<td>Reflective index of window materials</td>
<td>-</td>
<td>1.51</td>
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### Electrical and optical characteristics (Ta=25 °C)

<table>
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<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Spectral response range</td>
<td>λ</td>
<td></td>
<td>550 to 1050</td>
<td>-</td>
<td>-</td>
<td>nm</td>
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<tr>
<td>Peak sensitivity wavelength</td>
<td>λp</td>
<td></td>
<td>840</td>
<td>-</td>
<td>-</td>
<td>nm</td>
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<tr>
<td>Photon detection efficiency*2</td>
<td>PDE</td>
<td>λ=910 nm</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>%</td>
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<td>Dark count*3</td>
<td>Vop</td>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>kcps</td>
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<tr>
<td>Breakdown voltage</td>
<td>VR</td>
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<td>-47.5</td>
<td>-42.5</td>
<td>-37.5</td>
<td>V</td>
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<tr>
<td>Recommended operating voltage</td>
<td>Vop</td>
<td></td>
<td>-</td>
<td>Vbr - 5</td>
<td>-</td>
<td>V</td>
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<tr>
<td>Gain</td>
<td>M</td>
<td>Vop</td>
<td>-</td>
<td>1.0 x 10⁶</td>
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<td>-</td>
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<td>Temperature coefficient of Vop</td>
<td>ΔTVOP</td>
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<td>47</td>
<td>-</td>
<td>-</td>
<td>mV/°C</td>
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<td>Frame rate</td>
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<td>10</td>
<td>-</td>
<td>-</td>
<td>kfps</td>
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<td>PLL frequency</td>
<td>PLL</td>
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<td>200</td>
<td>220</td>
<td>MHz</td>
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<td>TDC full-scale range</td>
<td>FPLL=200 MHz</td>
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<td>-</td>
<td>-</td>
<td>10.24</td>
<td>μs</td>
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<td>TDC resolution</td>
<td>FPLL=200 MHz</td>
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<tr>
<td>TDC Jitter</td>
<td>FWHM, FPLL=200 MHz</td>
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<td>-</td>
<td>135</td>
<td>-</td>
<td>ps</td>
</tr>
</tbody>
</table>

*2: Photon detection efficiency does not include crosstalk or afterpulses.
*3: Threshold=0.5 p.c.

Note: The above characteristics were measured the operating voltage that yields the listed gain in this catalog. (See the data attached to each product.)
SiPM imaging array, product example by Hamamatsu

Demo units, together with evaluation and interface boards, are available to potential users.
Future Applications for SPAD Arrays

Quantum Technology – Quantum Key Distribution

Solid State Flash LiDAR

Brain Activity Monitoring
1. Photon counting can be a preferred detection technique when the incident light level is low.
2. SPAD and SiPM are well-suited for photon counting.
3. SPAD and SiPM image sensors are being developed.
4. Research and development continues to extend the detection into the IR regime.
5. Integration of ASICs with the SPAD or SiPM imagers is the most cost-effective approach. Hamamatsu provides support and will work with individual customers to provide solutions.
Join Us for 10 Weeks of FREE Photonics Webinars (17 Topics)

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<th>Week #</th>
<th>Weekly Topics</th>
<th># of Talks</th>
<th>Talk #1 Date</th>
<th>Talk #2 Date</th>
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<tr>
<td>1</td>
<td>Introduction to Photodetectors</td>
<td>2</td>
<td>26-May-20</td>
<td>28-May-20</td>
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<tr>
<td>2</td>
<td>Emerging Applications - LiDAR &amp; Flow Cytometry</td>
<td>2</td>
<td>2-Jun-20</td>
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<td>Understanding Spectrometer</td>
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<td>9-Jun-20</td>
<td>11-Jun-20</td>
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<td>Introduction to Image Sensors</td>
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<td>30-Jun-20</td>
<td>02-Jul-20</td>
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<td>1 Week Break</td>
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<td>8</td>
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<td>9</td>
<td>Photon Counting Detectors – SiPM and SPAD</td>
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<td>11-Aug-20</td>
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<td>10</td>
<td>Using SNR Simulation to Select a Photodetector</td>
<td>1</td>
<td>18-Aug-20</td>
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Thank you

Thank you for listening.

Contact information:

piatek@njit.edu