# Photon number resolving capability of qCMOS camera for Raman spectroscopy and imaging

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## Introduction of qCMOS

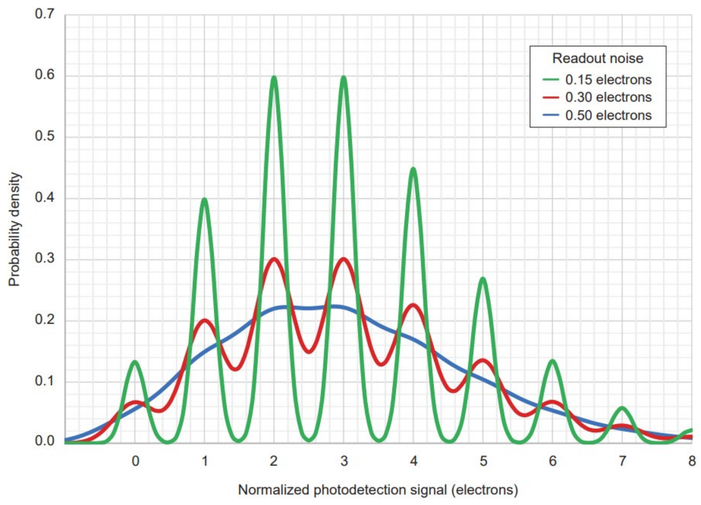
Introducing the new qCMOS

ORCA-Quest

- **Unprecedented Performance**
- **Ultimate sensitivity**
- **Photon number resolving capability**

| LOW READOUT NOISE | HIGH QE | HIGH RESOLUTION | HIGH SPEED |
|---|---|---|---|
| **0.27** ELECTRONS RMS | **90%** @475 nm | **4096 × 2304** | **120** FRAMES/S |
| *Ultra-Quiet Scan* | *Back-illuminated qCMOS* | *9.4 Megapixels* | *@4096 x 2304 (16 BIT) STANDARD SCAN* |

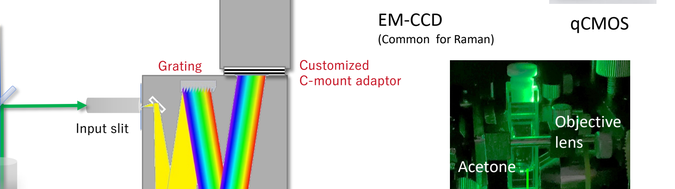
- What does “Photon number resolving” mean ?
  - Photon number resolving is unique and quite different from single photon counting.
  - The existing photon counting cameras like EM-CCD can never do photon number resolving because of their excess multiplication noise.
  - The following graph shows the probability distribution of the observed photoelectrons with a mean of N = 3 photoelectrons, and three different values of the readout noise. The smaller the readout noise is the deeper are the valleys between the photoelectron peaks. If the CMOS sensor can reduce the readout noise, it enables photon number resolving.




## qCMOS capability for Raman imaging

- Raman imaging method qCMOS can be beneficial

| | 1. Point scan method | 2. Line scan method | 3. Area scan method |
|---|---|---|---|
| Detection area | Small | Middle | Large |
| Scan speed | Slow | Middle | Fast |
| Spectral resolution | High | High | Low |
| Spatial resolution | Depends on scan pitch | Depend on scan pitch | Depend on camera |
| Focus | Good | Depend on sample | Depend on sample |
| Detection | Spectrometer + line sensor | Spectrometer + camera | Band-pass filter + camera |
| Products | Many | Some | Very few |




1. Point scan method : **NG**
   qCMOS has too many vertical pixels with small pixel size compared to common sensors for Raman. Digital binning of CMOS camera accumulates readout noise of each pixel, which might lead to lower sensitivity, low throughput.
2. Line scan method : **OK**
   The method does not use binning function, so we can enjoy benefit from qCMOS such as pixel size, pixel number, low noise, high QE etc.
3. Area scan method : **OK**
   Same as the line scan method. This method could be evaluated from ordinal SN simulation.

We want to evaluate the benefit quantitatively by using Quest on “ line scan method”. Especially, “spectral SN” is practical for the evaluation.

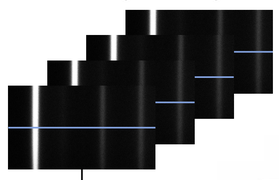
- Assumed line scan type Raman imaging systems
  - We tested what the effect can be brought by replacing EMCCD, a common camera for Raman imaging, to qCMOS for line scan type Raman imaging system.
  - 1st assuming case is **retrofit system** where there is no change of the optics and spectrometer and only a camera is replaced.
  - 2nd assuming case is **customized system** where the optics and spectrometer is optimized for qCMOS.



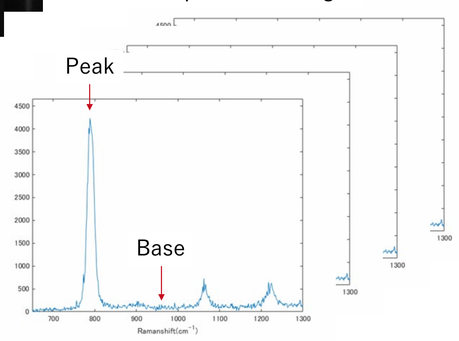

## Evaluation of $SN$, $SN_{sp}$

- How to evaluate SN (Signal-to-noise ratio)
  - Create a data set of 30 images
  - Create a spectrum from a single line in the center of the image
  - We evaluate SN and spectral SN as shown below. (I: Intensity, σ: standard deviation)
    - ✓ $SN = \frac{I_{peak}}{\sigma_{peak}}$ **(Conventional SN)**
    - ✓ $SN_{sp} = \frac{I_{peak}}{\sigma_{Base}}$ **(Spectrum SN)**

Raman image 30 images



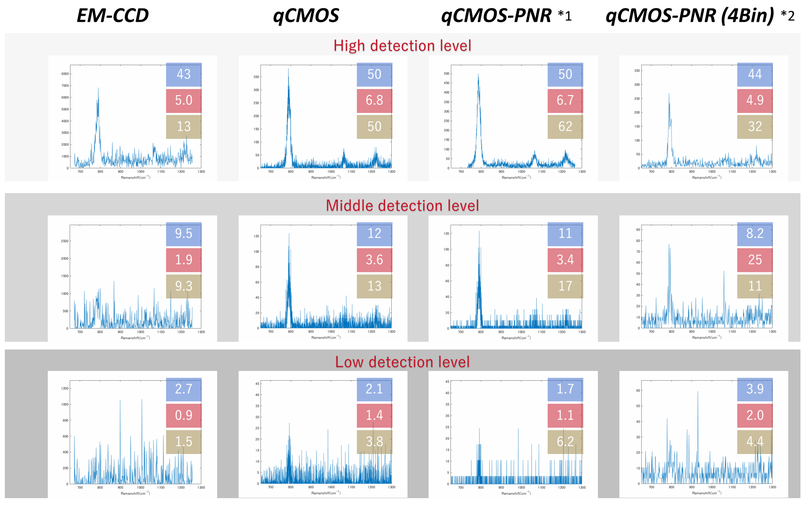
Raman spectrum 30 images




- Spectrum comparison under condition of same PN (photon number) / pixel

: $PN$ @peak ch.
: $SN$
: $SN_{sp}$

***EM-CCD*** ***qCMOS*** ***qCMOS-PNR*** *1 ***qCMOS-PNR (4Bin)*** *2




*1) The term “PNR” means Photon number resolving. PNR mode outputs the number of photoelectrons from Digital output.
*2) The term "4Bin" means treating 16 adjacent pixels as one big pixel (arranged in 4x4 pixels)

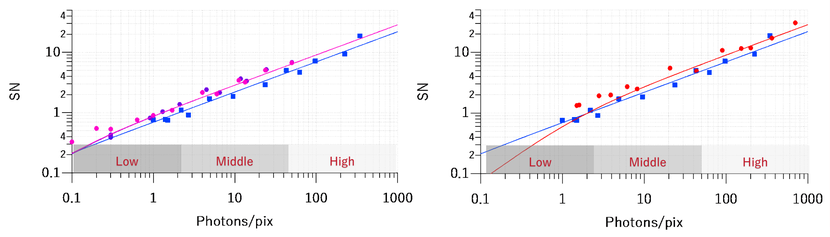
- $SN$ comparison under same PN/pix condition

### Customized system

*EM-CCD vs qCMOS vs qCMOS-PNR*

### Retrofit system

*EM-CCD vs qCMOS-PNR (4bin)*
*[comparison under comparable pixel size]*




- Theoretical SN data have been simulated.
- The measured SN and the Theoretical SN matched within the tolerance of error.
- Consideration of $SN$
  - ✓ In middle to high photons detection range, qCMOS camera is the better than EM-CCD due to the excess noise of EM-CCD.
  - ✓ In low photons detection range, qCMOS-PNR is the best because of the noise level.
  - ✓ In low photons detection range, qCMOS(4Bin)-PNR are lower than EM-CCD since noise is added depending on the number of binning channel

Markers : Measured data
Line : Simulated data

: *EM-CCD*
: *qCMOS*
: *qCMOS-PNR*
: *qCMOS-PNR (4Bin)*

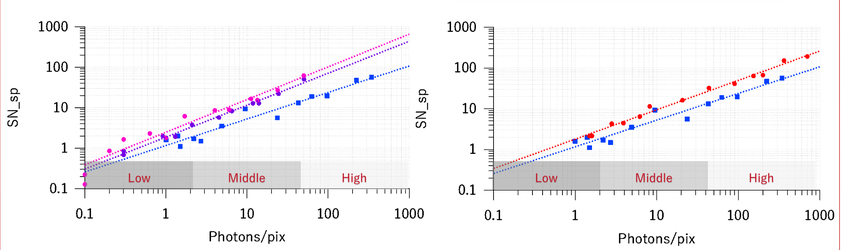
- $SN_{sp}$ comparison under same PN/pix condition

### Customized system

*EM-CCD vs qCMOS vs qCMOS-PNR*

### Retrofit system

*EM-CCD vs qCMOS-PNR (4bin)*
*[comparison under comparable pixel size]*




- The approximation curve is made from fitting of the measurement data.
- Consideration of $SN_{sp}$
  - ✓ In middle to high photon detection range, qCMOS camera is better than EM-CCD because of the noise performance, and qCMOS-PNR is the best.
  - ✓ In low photon detection range, qCMOS-PNR is the best because of the noise level.

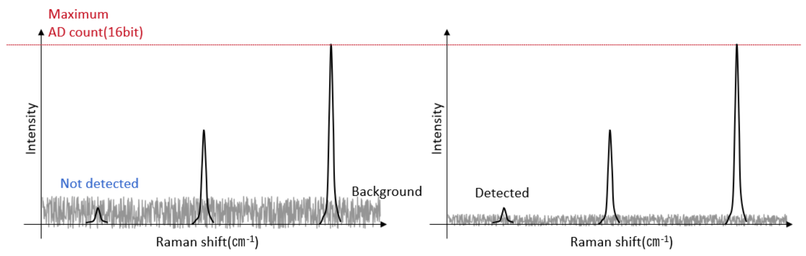
Markers : Measurement data
Dot line : Approximation curve

: *EM-CCD*
: *qCMOS*
: *qCMOS-PNR*
: *qCMOS-PNR (4Bin)*

## Spectral dynamic range

An important point of spectral analysis is how many Raman bands in wide intensity range can be detected.

- ✓ Minimum detection limit is determined by spectrum SN, $SN_{sp}$. Assume that the Raman signal can be detected when $SN_{sp} > 2$.
- ✓ Maximum detection limit can be adjusted by high intensy Raman band and maximum AD counts of a detector

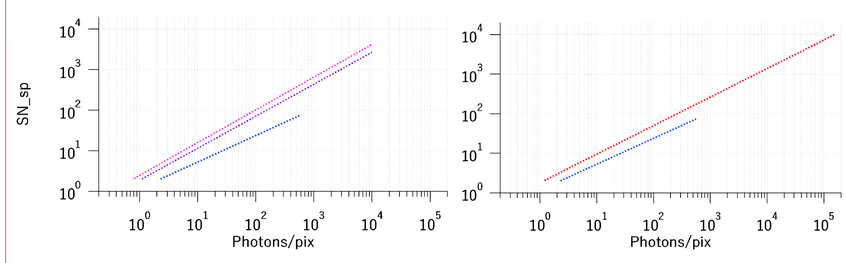



### Customized system

*EM-CCD vs qCMOS vs qCMOS-PNR*

### Retrofit system

*EM-CCD vs qCMOS-PNR (4bin)*



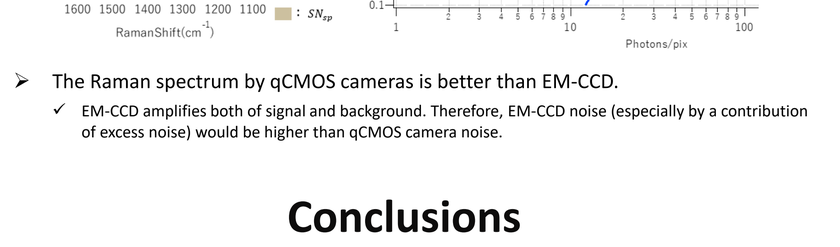

- The spectral dynamic range of qCMOS is larger than that of EM-CCD.
  - ✓ The spectral dynamic range of EM-CCD is deteriorated by EM gain amplification.*
  - ✓ The spectral dynamic range is shown in the table below.

*In this experiment, EM gain is 640x.

| Dynamic range | EM-CCD | qCMOS | qCMOS-PNR | qCMOS-PNR (4Bin) |
|---|---|---|---|---|
| PN | 2.3~570 | 1.1~10K | 0.8~10K | 1.2~160K |
| AD count | 240~60K | 7~60K | 5~60K | 7~970K |

Dot line : Approximation curve
: *EM-CCD*
: *qCMOS*
: *qCMOS-PNR*
: *qCMOS-PNR (4Bin)*

- The figure attached below shows the spectral dynamic range when measurement conditions are set to the maximum AD count for a sample with no background.

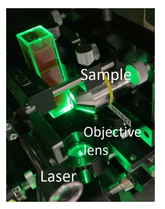



Quest is higher dynamic range than EM-CCD
>> As a model of customized system

Quest-PNR (4Bin) is higher dynamic range than EM-CCD because of PNR-binning effect.
>> As a model of retrofit system

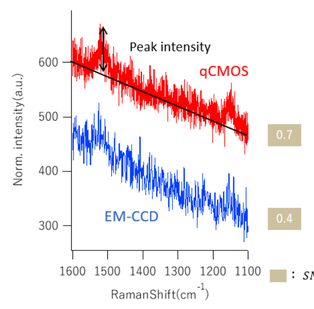
## Samples with background emission

- For the SN evaluation, we used acetone which do not have background emission such as fluorescence.
- In this section, we measured Raman spectrum of Lycopene contained in tomato juice, which does have fluorescence around Raman resonance wavelength.

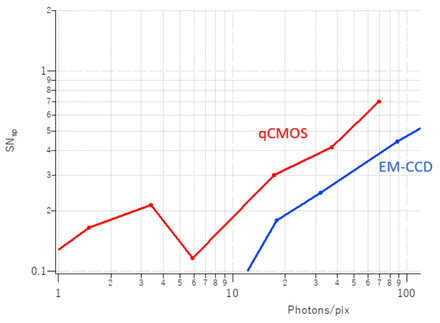



Tomato juice

*Raman spectra for Tomato juice*




*$SN_{sp}$ curve*




- The Raman spectrum by qCMOS cameras is better than EM-CCD.
  - ✓ EM-CCD amplifies both of signal and background. Therefore, EM-CCD noise (especially by a contribution of excess noise) would be higher than qCMOS camera noise.

## Conclusions

**Table: Consideration of line scan type Raman imaging system performance of replacing EM-CCD to qCMOS**

| Contents | | Retrofit | Retrofit (w binning&PNR) | Custom design |
|---|---|---|---|---|
| **Mechanics** | **Lens** | — | — | Use a proper designed lens |
| | **Spectrometer** | — | — | Use a short focal length or low ruling number of grating |
| | **Input split** | — | — | Depends on measurement design |
| | **Adaptor** | Custom made | Custom made | Custom made |
| **Spatial resolution** | | Better | Similar | Similar |
| **Detectable light intensity** | | Worse | Similar | Similar |
| **SN** | | Worse | Better or Similar | Better |
| **Speed** | | Worse | Better or Similar | Better |
| **Spectral resolution** | | Similar | Similar | Similar |
| **Spectral dynamic Range** | | Better | Better | Better |
| **FOV range** | | Better or Similar | Better or Similar | Better or Similar |

- For retrofit system, the performance of qCMOS-PNR (4Bin) is better than EM-CCD.
- For customized system, the performance of qCMOS and qCMOS-PNR is better than EM-CCD.

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