Detection of Optical Radiation.
Photodiode arrays and CCD cameras.
Class lecture and ch.22

Lecture 28

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C. Davis, “Lasers and Electro-optics”
Photodiode Array (PDA)

A Photodiode Array (PDA) is a series of silicon detectors lined up in a row. Each diode element is reverse biased and is charged like a capacitor. Incident photons deplete this charge until the diode is readout during the readout cycle. Then each diode is recharged. The signal is the current needed to refresh the diodes.

- Coverage or resolution
  - Coverage (nm) = Reciprocal lin. disp. (nm/mm) x width of slit (mm)
  - Resolution (nm) = Coverage (nm) / number of pixels

Coverage or resolution with PDA you get broad wavelength coverage or high resolution, but not both.

- The ability to resolve a spectral line depends upon the slit width length, but is limited by the diode width. For a slit width less than the diode width, there can be several images on one diode that cannot be differentiated. The diode width is limited by the slit width resolution is limited by the diode width resolution is limited by the diode width. The wavelength bandwidth of fewer than four pixels is not always enough to resolve a peak.
Example:

Ree. linear dispersion = 50 \text{ nm/mm}

Array size = 25.6 mm

Diode size = 25 \text{ \mu m} \text{ width}

\[ \text{Continuous Spectrum:} \]

\[ \frac{\text{Resolution/diode}}{\text{pixel bandwidth}} = \frac{\text{total coverage/\# diodes}}{\text{Ree. lin. dispersion x array size/\# diodes}} = \]

\[ = \frac{50 \text{ nm/mm} \times 25.6 \text{ mm}}{1024 \text{ diodes}} = \]

\[ = 1.95 \text{ \mu m/diode} \]

\[ \text{Emission Spectrum:} \]

1) Given 19.9 \text{ \mu m} slit and assuming 1:1 slit image

   a) Given 10 \text{ nm} slit, magnification at the exit:

   \[ \text{diode width} = \frac{25 \text{ \mu m/diode}}{10 \text{ \mu m/image}} = 2.5 \text{ images/diode} \]

   \[ \text{slit width} = \frac{25 \text{ \mu m/diode}}{10 \text{ \mu m/image}} = 2.5 \text{ images/diode} \]

   b) Resolution/image = \text{dispersion} x \text{slit width} = \]

   \[ = 50 \text{ nm/mm} x 0.01 \text{ mm/image} = \]

   \[ = 0.5 \text{ nm/image} \]

   c) Resolution/diode = \text{resolution/image x images/diode} = \]

   \[ = 0.5 \text{ nm/image} x 2.5 \text{ images/diode} = \]

   \[ = 1.25 \text{ nm/diode} \]

2) Given 10 \text{ \mu m} slit:

   a) 25 \text{ \mu m/100 \mu m} = 0.25 \text{ images/diode} \]

   b) 50 \text{ nm/mm} x 0.1 mm = 5 \text{ \mu m/image} \]

   c) 5 x 0.25 = 1.25 \text{ \mu m/diode} \]

3 to 4 diodes are needed for good resolution of a slit image, resolution of the image may be limited by the pixel width.
Quantum efficiency: the ratio of number of photon/electrons produced to the number of photons impinging on a photosensitive surface.

Dynamic range: the ratio of the smallest distinguishable measurable charge to the largest before saturation. The system dynamic range is determined by the A/D conversion of the full-scale output of the final amplifier stage. Usually 12 to 16 bit converters are used.

Linear response is usually due to amplifier problems.

Noise Sources

1) Shot noise = photon noise: is due to the statistical nature of light. It is equal to the square root of the number of electrons generated.
2) Reset noise: due to non-uniformities in the pixels.
3) Amplifier noise: electrical variations in amplifiers.
4) Bias charge: due to introduction of an additional charge.
5) Read-out noise: due to variations in the charge current of each pixel in the detector.
6) Dark signal: generated by thermal agitation. Dark signal doubles with every $8$ to $10^6$ increase above $25^\circ$.

PDA Characteristics
Two dimensional view of silicon lattice

Silicon lattice in various states of excitation.

Each atom of silicon is covalently bonded to its neighbor.

Energy greater than 1.1 eV is required to break a bond and create e-h pair.

Under constant illumination, an equilibrium is set up between the rates of incoming flux and charge recombination.

The shorter the shorter the penetration depth into silicon Si, transparent \( \lambda > 400 \text{nm} \).

Bonds can be broken by thermal agitation. At \( T = 300 \text{K} \) ~ 50 bonds per \( \text{cm}^3 \) are broken & recombine on a continuous basis.
The charge is collected in a CCD also but the operating mode is different than in a PDA. Light incident on the CCD detector frees an electron which drifts toward the depletion region where it is collected. Whereas a PDA consists of individual diode elements which are each read out individually, the CCD is one continuous material. Individual pixels or picture elements are defined within a readout column by three electrode gates of varying a applied voltage. The center gate has a greater potential and is therefore where the charge is collected.

Potential Well Formation

The voltages applied through these gates are then clocked so as to move the charge across the pixels to the serial register.
Potential Well Concept

In order to measure the "e" charge produced by incident photons it is necessary to provide a means for collecting the charge. A thin layer of silicon dioxide is grown on a section of silicon and a conductive gate structure is applied over the oxide. Positive electrical potential to the gate creates a depletion region where free electrons can be stored.
CCD Principles. Principle of Charge Transfer.

Fig. 3. Charge transfer in a three-phase CCD using the potential well concept.

- A single crystal of silicon is sliced into very thin sheets of several cm².
- A matrix arrangement of oxide and gate structures are fabricated—many thousands of potential wells are established across a large area of silicon.
- Gate structure is arranged in width multiple phases, so that potential wells can propagate through a silicon sheet.
Two dimensional charge concept.

Typical 512 x 512 CCD.

- Two-dimensional array of potential wells is called parallel register wells.
- An image that is focused on the parallel register produces a pattern of charge.
- The total integrated flux incident on each photosite.
- Serial register is a one-dimensional CCD.
- CCD plays an important role during CCD readout.
CCD Readout Sequence

A sequence of changing gate potentials causes all charge packets stored in the parallel register to be shifted in parallel one row toward the serial register.

The CCD is exposed to light. An electronic image accumulates as a pattern of charge in the parallel register. The CCD is ready to be read out.

All rows are shifted in parallel. The top row is shifted into the serial register.

Once in the serial register, pixels are individually shifted toward the output node.

The next row can be shifted into the serial register after that register is cleared.

CCD readout.

The charge stored in the top row is shifted from the parallel register into the serial register.

Once in the serial register, charge packets are shifted toward the output amplifier.

The output amplifier produces a measurable signal proportional to charge in each charge packet.

After serial register is emptied of charge a second row of charge is shifted.

10
Thick and Thinned CCDs

A. Light normally enters the CCDs through gates of 11 register. Gates are made from polysilicon which is opaque at λ < 1000μm.

B. Using acid etching techniques to uniformly thin a CCD to a thickness of ~10μm and focus an image on the backside of the CCD register where there is no gate structure.
CCD Spectral Response

Typical Quantum Efficiency curves of standard and backthinned CCD chips with and without a UV coating.

To achieve UV response (190-400 nm), the CCD surface must be coated with a very thin layer of an organic converter which absorbs UV radiation and re-emits it at longer wavelengths.

To eliminate loss of response due to absorption by and reflection from the polysilicon gates, special CCD arrays that can detect through the rear surface of the CCD are used.
Well Capacity

Maximum # of e⁻ that can be contained in a single "potential" well without causing excessive spill-over to adjacent regions (blooming).

For CCD with a pixel size > 20µm:
typical well capacity 400,000 - 750,000
for size < 10µm:
well capacity 40,000 - 80,000.

Dynamic range
17 bits or about 130,000:1

Signal-to-noise (S/N) performance

\[ N_T = \text{overall noise} \]
\[ N_T = \sqrt{N_e^2 + N_d^2 + N_{ph}^2} \]

- \( N_e \) = Readout noise of the CCD
- \( N_d \) = Dark charge noise
- \( N_{ph} \) = Photon shot noise.

1) \( N_e \) depends on scan rate, electronics design, size of the pixel, temperature.
2) \( N_d \) = Dark charge noise
   \[ N_d = (S_d)^{1/2} \]
3) \( N_{ph} \) = Photon shot noise - statistical fluctuations in the flux of the measured signal \( S_{ph} \)
   \[ N_{ph} = (S_{ph})^{1/2} \]
Analysis of Instrumental Sensitivity/Detectability

Let us now analyze the proposed configuration of the Raman instrument, in terms, its sensitivity, signal-to-noise performance (S/N), and capability of functioning with diode laser excitation as low as 150 mW power. It is assumed that we use the currently state-of-the-art back-illuminated CCD chip, CCD 15-11 (EEV catalog). It has the following characteristics: format, 1024×256; pixel size, 27×27 μm; active area, 27.6×6.9 mm; quantum efficiency of CCD (QE) @800 nm, ~ 0.8; dark charge (SD) for cooling temperature @ -120°C, SD = 0.00015 electrons/pixel-second; and readout noise, NR = 10 electrons. Assume the gain setting is: 10 electrons = 1 A/D count.

We examine sensitivity/detectability of the system for 20 min = 1200 seconds accumulation time with “supersize” pixel size ~80 pixels (256/3 where a spectrum is accumulated in a 1024×80 format). After 1200 seconds of accumulation, SD = 0.00015 × 1200 (seconds) × 80 (pixels) = 15 electrons = 1.5 counts. Dark charge noise, ND = (SD)1/2 = (15)1/2 ~ 4 electrons = 0.4 counts. The total noise associated with the acquisition of a spectrum by the CCD, NT, maybe defined as:

\[
N_T = \left[ N_R^2 + N_D^2 + N_{ph}^2 \right]^{1/2}
\]

where NR = readout noise of the CCD; ND = dark charge noise; and Nph = photon shot noise. If we ignore photon shot noise at very low light levels, then

\[
N_T \equiv \left[ 1 + 0.4^2 \right]^{1/2} \sim 1.1 \text{ counts}.
\]
It is important to note that usually the total noise of the CCD camera is defined in electrons (or counts) \(\sqrt{\text{rms}}\) (root-mean-square or standard deviation). For determination of the lowest detectable signal it is more meaningful to consider the peak-to-peak variations of this noise, which is about five times higher. Hence,

Since 1.1 counts \(\text{rms}\) usually means \(1.1 \times 5 = 5.5\) counts peak-to-peak noise fluctuations, detectability, namely the smallest detectable signal, will be the signal that is equal to this noise fluctuation level. That is, \(N_T = 1.1 \text{ counts} = 5.5 \text{ counts (peak to peak)} = 55 \text{ electrons/0.8 (QE)} \sim 70\) photons. Thus, detectability is 70 photons, or 70 photons / \((1200 \text{ seconds} \times 80 \text{ pixels}) = 0.0007\) photon/second-pixel.
Let us compare this smallest detectable signal with the Raman signal resulting from a 150-mW diode laser excitation that enters the CCD through a 50 μm core graded-index fiber, similar to that described by Schoen (1994) (with losses of less than 3 dB through a 1-km long fiber). In this case the output power at the output end of the fiber is 40 mW. The number ($S_e$) of exciting photons per second with a wavelength 800 nm can be easily calculated as:

$$S_e = \frac{40 \cdot 10^{-3} \cdot (W) \cdot \frac{\text{m}}{\lambda}}{6.62 \cdot 10^{-34} \cdot (J \cdot s) \cdot 3 \cdot 10^8 \cdot (m/s) / 800 \cdot 10^{-9} (m)} = 16 \cdot 10^{12} \text{ (photons/sec)}$$

Assuming that the Raman signal from the sample of interest is rather small and is $\approx 10^{-10}$ with respect to the excitation radiation. Then the number of Raman photons will be $S_R = 16 \times 10^2$ photons/sec. Taking into account $\approx 30\%$ additional losses in the fiber, $\approx 10$-fold loss in the fiber-optic signal-collection system, and $\approx 50\%$ throughput of the spectrometer, the incoming Raman signal on the CCD chip will amount to $S_{R \text{ CCD}} = 55$ photons/second. Due to the fact that we illuminate 80 pixels, the incoming signal per pixel will be $\approx 0.7$ photon/second-pixel compared to a detectability of 0.0007 photon/second-pixel.

Thus, the signal obtained is $\approx 1000$ times larger than the smallest detectable signal of the chosen CCD chip. Therefore, the proposed instrument should be operable even with integration times as low as 30 seconds.