Photomultiplier Tubes and Photodiodes

- Fig. 9.1 shows a simplified model of the photomultiplier, including the two major components inside the tube.
    1) Photocathode: the photosensitive layer that converts incident light into low energy electrons.
    2) Electron multiplier structure: Collects electrons generated from the photocathode and multiplies then so that a simple scintillation pulse will give rise to 10^7-10^{10} electrons.

The Photocathode

The Photoemission Process:

- 3 stages of photocathode electron production:
    1) The absorption of the incident photon and transfer of energy to an electron within a photoemmissive material- the quantum energy for the scintillation photon ~ 3 eV (for blue light)
    2) The migration of the electron to the surface- the electron will lose energy through electron-electron collisions.
    3) The escape of the electron from the surface- this occurs by overcoming the potential barrier of the surface-vacuum interface (the work function). Which is < 3-4 eV for metals and <1.5-2 eV for a suitably prepared semiconductor.
- Due to the minimum barrier imposed in step 3) (from the finite barrier work function), the losses and thickness in step 2) should be minimized.
- Electrons can only travel ~ a few nm in metal or up to 25 nm in a semiconductor, but even this thickness is only semi-transparent to visible light and thus only a portion of the light is converted to electrons no matter how minimal the energy barrier is.
- Less than ½ the incident photons (at these thicknesses) will interact with the photosensitive portion of the cathode.
- For light absorption in a semiconductor:
    1) Light photon absorption elevates an electron from the normally populated valence band into the conduction band. The electron then loses energy (through lattice interactions-phonons) until it at a minimum in the conduction band energy.
    2) The electron affinity is the energy difference between the bottom of the conduction band and the higher electron potential outside the surface.
    3) For the electron to escape, it must reach the surface prior to losing enough energy (through phonon interactions) to drop below the electron affinity.
- If the electron does not make it to the surface before losing too much energy it may last in the conduction band (~ 100 ps) before recombining with the hole in the valence band.

- Use of negative electron affinity materials allows an electron to leave the surface, upon migration, even if it has reached the bottom of the conduction band.

Spontaneous electron emission:

- Also called thermionic noise.
- Normal conduction electrons will have some initial kinetic energy ~0.025 eV , but this has a distribution, so some may have energy exceeding the energy potential barrier.
- In metal this emission rate is low (~100/m^2*s), however in a semiconductor the lower potentials lead to higher spontaneous emission rates (10^6-10^8/m^2*s).
- This becomes a tradeoff between metals and semiconductors, where semiconductors are more photosensitive, but at the expense of higher noise.

Fabrication of photo cathodes:

- Can be opaque or semi-transparent, each having different geometry considerations.
- An important factor in application is the thickness uniformity, the corresponding changes in sensitivity can be a source of resolution losses in scintillation counters (an especially serious problem for large photomultiplier tubes).

Quantum Efficiency and Spectral Response:

- Sensitivity can be relayed in many ways.
- For DC light measurements, the overall photo cathode efficiency is defined as the current produced per unit light flux at the surface.

- Quantum Efficiency (QE):

$$QE = \frac{\#\ of\ \ photoelectrons\ \ emitted}{\#\ of\ \ incident\ \ photons}$$

- The QE will be dependent on the wavelength of the incoming light (Fig. 9.2)
- The design of the photo cathode should then be selected to have high QE over the range of expected wavelengths.

Electron Multiplication

Secondary Electron Emission:

- Electrons from the photocathode are accelerated and caused to strike the surface of an electrode, called a dynode. The process is repeated several times in a cascade, where electrons from a previous dynode interaction are accelerated toward another dynode.
- For each incident electron there can be more than one electron re-emitted.

- The overall photomultiplier factor for a single dynode is given by:

$$\delta = \frac{\#\ of\ \ \text{sec}\, ondary\ \ electrons\ \ emitted}{\#\ of\ \ primary\ \ incident\ \ electrons}$$

- Fig. 9.3 shows the change in δ given varying incident electron energy for various materials (δ~4-6 or even 10).

Negative Electron Affinity Materials (NEA):

- Materials such as GaP (gadolinium phosphate) with heavy p-type doping material (like zinc) can produce much higher gains.
- Note the change in the band positioning (relative to the potential required at the solid-vacuum interface) in Fig. 9.4 from using an NEA material.
- Note how this increases δ to 50-60 for excitation voltage (interstage) ~1000 V.

Multiple Stage Multiplication:

- To achieve gains ~10^6, a PM tube uses multiple stages.
- The photoelectrons are guided using the inter-stage voltage excitation, producing δ electrons (as a function of energy) at each of several stages.
- Overall gain ~ $\alpha\delta^N$, where N is the number of stages, and α is the fraction of all photoelectrons collected by the multiplier structure.
- For example, a conventional PM, δ=5 with α~1 for well designed tubes yields of 5^{10} (for 10 stages) ~10^7, whereas a high yield NEA tube δ=55 can produce the same output with only 4 stages.

Statistics of Electron Multiplication:

- δ is not required to be constant, so the output under fixed conditions may not produce constant output.
- We assume the yield for secondary electrons follows a Poisson distribution at a dynode.
- Then the mean # of secondary electrons at the first dynode is δ, and the standard deviation is $\sqrt{\delta} = \sigma$.
- Thus the relative variance (variance divided by the square of the mean) = 1/δ.
- And after N stages:

$$\frac{1}{\delta} + \frac{1}{\delta^2} + \frac{1}{\delta^3} + \ldots + \frac{1}{\delta^N} \cong \frac{1}{\delta - 1}$$

- If δ>>1 then the overall spread (relative variance) is dominated by the fluctuations in the yield from the first dynode, where the # of electrons is the smallest.
- In general this is not a good model for all PM tubes and it may be that differences in electron trajectories and dynode properties preclude a general model applicable for all PM tubes.

Photomultiplier Tube Characteristics

Structural differences:

- Fig. 9.7 shows some typical geometry for PM tubes.
- Fig. 9.8 shows a continuous channel electron multiplier (a PM tube with the equivalent of continuous dynodes).
- Fig. 9.9 shows a PM tube based on micro-channel plate electron multiplication (these have excellent timing properties).

Pulse Timing Properties:

- Since the time required for photoemission in the photocathode or secondary emission from the dynode is very short (~0.1 ns) the time characteristics of a PM tube are driven by electron trajectories.
- Electron transit time- the average time difference between the arrival of a photon at the photocathode and the collection of the subsequent burst at the anode.
- However the transit time is not so important since that would just introduce a delay.
- Spread in transit time is the variable spread in transit time, which determines the time width of the pulse of the electrons arriving at the anode of the tube and is affected by the geometry and the initial number of photoelectrons per pulse.
- Maximum ratings: maximum voltage and current for a PM tube (Table 9.1).