transit time can be shortened. On the other hand, the capacitance has to be kept low which means a larger depletion width. As seen, a trade-off has to be made for the overall optimization.

The signal of the photocurrent should be maximized for sensitivity. The basic metric is the quantum efficiency, defined as the number of carriers produced per photon, or

$$\eta = \frac{I_{ph}}{q\Phi} = \frac{I_{ph}}{q}\left(\frac{h\nu}{P_{opt}}\right) \tag{2}$$

where I_{ph} is the photocurrent, Φ is the photon flux ($= P_{opt}/h\nu$), and P_{opt} the optical power. The ideal quantum efficiency is unity. The reduction is due to current loss by recombination, incomplete absorption, reflection, etc. Another similar metric is the responsivity $\mathscr{R}$, using the optical power as the reference,

$$\mathscr{R} = \frac{I_{ph}}{P_{opt}} = \frac{\eta q}{h\nu} = \frac{\eta\lambda(\mu m)}{1.24} \quad \text{A/W}. \tag{3}$$

To further improve the signal, some photodetectors have an internal gain mechanism. Comparison of the gains of common photodetectors are shown in Table 1. Gain as high as 10^6 can be achieved. Unfortunately, high gain also leads to higher noise which is the following topic.

Apart from a large signal, low noise is also important as it will ultimately determine the minimum detectable signal strength. That is why we often speak of the signal-to-noise ratio. There are many factors that contribute to noise. The dark current is the leakage current when the photodetector is under bias but not exposed to the light source. One limitation on the device operation is temperature so the thermal energy should be smaller than the photon energy ($kT < h\nu$). Another source of noise is from background radiation, such as black-body radiation from the detector housing at room temperature if not cooled. Internal device noise includes thermal noise (Johnson noise), which is related to the random thermal agitation of carriers in any resistive device. The shot noise is due to the discrete single events of the photoelectric effect, and the statistical fluctuations associated with them. This is especially important for low light intensity. The third is due to flicker noise, otherwise known as 1/f

Table 1 Typical Values of Gain and Response Time for Common Photodetectors

Photodetector		Gain	Response time (s)
Photoconductor		1–10^6	10^{-8}–10^{-3}
Photodiodes	*p-n* junction	1	10^{-11}
	p-i-n junction	1	10^{-10}–10^{-8}
	Metal-semiconductor diode	1	10^{-11}
CCD		1	10^{-11}–10^{-4}*
Avalanche photodiode		10^2–10^4	10^{-10}
Phototransistor		$\approx 10^2$	10^{-6}

* Limited by charge transfer. Large integration time is an advantage for CCD for high sensitivity.