Detectors

18. Lecture, 2 November 1999

18.1 Detection of light

By “detection,” we mean the absorption of light and the associated production of something we can measure and store. Usually, we use detectors that turn light into electric charges and currents, so that the “answer” comes out in terms of currents or potential differences whose values are related to how much light was incident on the device. This is not the only way to store and read electric charge – another way, for example, is to create the charges by absorption of light, and have those charges trigger chemical reactions; this is how photographic emulsions work. The most sensitive detectors, however, happen to be those that turn light into electrical currents, and since astronomers generally need the most sensitive detectors, we need to understand this class of devices.

In principle, one must learn a fairly large amount of solid-state physics and materials science to understand the details of the operation of any astronomical detector. Here we will only discuss simple pictures of their workings; we’ll discuss their *noise* and *sensitivity* in gory detail, though.

18.2 Photodetectors

Photodetectors are devices in which light, in the form of photons (rather than waves), is used to produce electrons for conduction, by having the photon liberate a previously bound electron (one not participating in conduction). The class of photodetectors includes, among other devices,

- Vacuum-tube photodiodes, photomultipliers, and microchannel plates;
- Semiconductor photodiodes;
- Intrinsic and extrinsic photoconductors;
- Blocked-impurity-band (BIB) detectors and solid-state photomultipliers (SSPMs);
- Superconductor-insulator-superconductor (SIS) tunnel junctions.

They have these two features in common:

1. an *energy gap* E_g between the states for conduction and non-conduction electrons, that prevents the accumulation of a lot of small amounts of energy from leading to the production of conduction electrons, and instead requires the provision of energy greater that the gap energy, all at once - in the form of a photon (Figure 18.1). Ideally, the energy gap ensures that no current flows *unless* photons with energy $h\nu \geq E_g$ shine on the device. The paradigm for this energy gap is the *binding energy* of an atom; production of a free (conduction) electron from an atom is then simply *photoionization*.
2. When light shines on them, say a power P_S at a frequency $\nu = c / \lambda$ such that $h\nu \geq E_g$, an electrical current of the form

$$I_S = \frac{\eta G e P_S}{h\nu} \tag{18.1}$$

is produced (Figure 18.2). I_S is called the *photocurrent*. $P_S / h\nu$ is simply the number of photons incident on the detector per unit time. η, called the *quantum efficiency*, is the fraction of the incident photons that the detector absorbs (and thus $\eta \le 1$, since one can't absorb more than what is incident). G, called the *photoconductive gain*, is the number of electrons produced by photon absorption, that get "collected" by traveling all the way to the electrodes leading away from the device. G can thus be less than unity – for instance, if it (the electron) gets captured before it makes it to the electrode – *or* greater than unity – for instance, if the electron can *collisionally* produce other electrons, providing the gap energy from their kinetic energy.

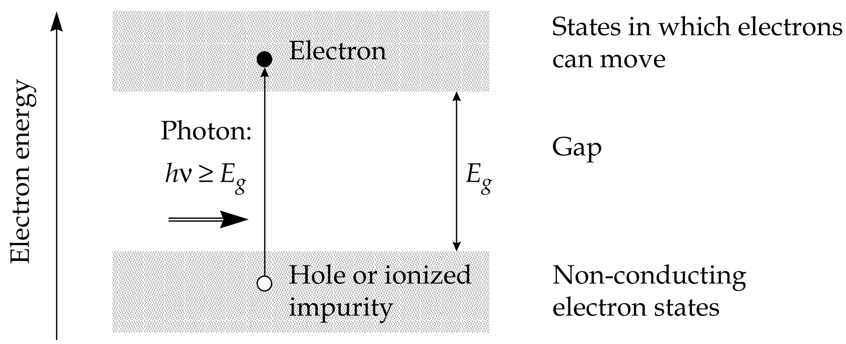

Figure 18.1: schematic diagram of absorption of an incident photon, and production of conduction electron and a hole or ionized impurity, in a photodetector.

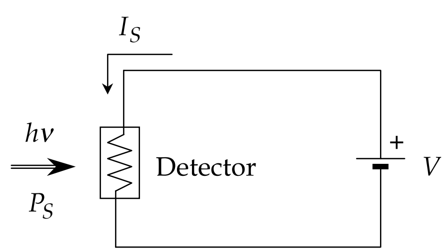

Figure 18.2: incident power P_S in photons of energy $h\nu$, and photocurrent I_S, in a photodetector (represented by a resistor) with *bias* voltage V.

Good photodetectors are those *with large values of the quantum efficiency*, η. A low value of η means that incident photons are being rejected, rather than absorbed, which would clearly make it difficult to detect faint astronomical objects. As we shall see in a few lectures, though, it is possible for a photodetector to be good *without* a large value of the photoconductive gain G.

The value of η or G that a particular detector has is determined by the light-absorption and conduction properties of the material it's made from - this is where the solid-state physics details come in. We'll gloss over these details, and mention simply the values of η and G obtained for the best devices. In Figure 18.3 we show the coverage of the electromagnetic spectrum by the detectors used in astronomy; Table 18.1 is a list of the details of composition, origin of the gap, and values of η and G achieved in modern detectors.

Another figure, often quoted for photodetectors, is the *current responsivity*, ***R***:

$$R \equiv \frac{I_S}{P_S} = \frac{e}{h\nu}\eta G \quad . \tag{18.2}$$

R is just proportional to the product ηG. Its units, conventionally, are AW^{-1}.

18.3 Thermal detectors

Most of our discussions of sensitive detection of light will be based on photodetectors. In so doing we will leave out the details of another important class of devices, *thermal detectors*, also known as *bolometers.* The following superficial discussion is offered by way of introduction to these detectors.

If one has a good thermometer, and a good absorber of light of any wavelength, one can put the two together to make a detector: the light heats up the absorber. That's how bolometers work. They are often made in "composite" form, with the absorber and thermometer in good thermal contact but made of different materials. Electronic materials that have large temperature coefficient of resistance, dR/dT, are used as thermometers; so that very small heat pulses show up as large changes in voltage at constant current. For instance, extrinsic silicon or germanium, doped almost into the metallic regime and operated at a very low temperature (0.1 K or below), has very large dR/dT. The bolometers used most commonly in wide-bandwidth applications at far-infrared and submillimeter wavelengths have such semiconductor thermometers. The onset of superconductivity in certain metals and ceramics offers another situation of very large dR/dT. In this case the thermometer is made of a superconducting material, and the bolometer is thermally stabilized very precisely at its superconducting transition temperature. Finally, there are *hot-electron* bolometers. These usually consist of lightly-doped semiconductors with very high electron mobilities (like InSb, GaAs, HgCdTe), in which the conduction-band electrons aren't in very good thermal contact with the host lattice. Heat added to the electron system leads to a resistance change: typical electron velocities change as a result of heating, and the electrons scatter less effectively on ionized impurities. All of the most sensitive astronomical bolometers – semiconductor, superconducting transition-edge, and hot-electron – need to be operated at cryogenic temperatures, mostly $T \leq 4$ K.

The responsivity of a bolometer is determined by its thermometer's dR/dT, the heat capacity c of absorber and thermometer, and the thermal conductance g between the bolometer and heat bath. These parameters are chosen by the designer according to the tradeoffs among responsivity and speed. Responsivity is larger with larger dR/dT, and smaller c and g; the speed of response is faster with *larger g*.

One important virtue of bolometers is that they can be made to work at *any* wavelength, since all that must be done is to turn the light into heat, and this can usually be done with good efficiency $(\eta \geq 0.5)$. Thus the ideal thermal detector is quite competitive in sensitivity with the ideal photodetector at any wavelength. However, it turns out to be much harder to achieve ideal performance with bolometers than with photodetectors, and thus photodetectors tend to be used whenever available. The principal drawbacks of bolometers are fragility, difficulty of manufacture in the form of arrays, necessity of operation at temperatures so low as to be extremely difficult to reach, and tendency to excess noise.

18.4 Astronomical detectors

Figure 18.3 and Table 18.1 contain a summary of today's most important astronomical detector types, and the wavelengths at which they are used. The more important details of the operation of the photodetectors on these lists are presented in the following sections, presented as **optional** reading.

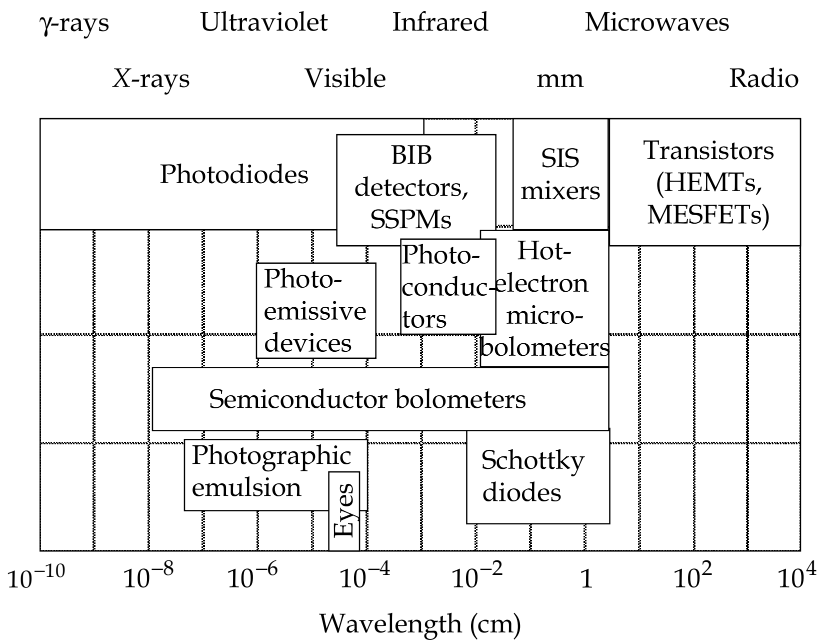

Figure 18.3: modern astronomical detectors and the ranges in wavelength over which they find use.

Table 18.1: (following pages): roll call of modern astronomical detectors and arrays.

Device	Nature of gap	Wavelengths covered	Typical η	Typical *G*	Materials	Examples, comments
Semiconductor photodiode	Semiconductor band gap	< 10 μm	0.7-1	1	Si, Ge, InSb, HgCdTe	Visible-wavelength CCDs, infrared DRO arrays, Ge γ-ray detectors; imaging X-ray, UV, visible and near-infrared detectors on AXAF, HST, SIRTF, *etc.*
Avalanche photodiode	Semiconductor band gap	< 1 μm	0.7-1	10^6	Si	Large gain dispersion involves excess noise.
Blocked-impurity-band (BIB) detector	Impurity ionization energy	< 200 μm	0.1-0.7	1	Si:As, Si:Sb, Si:Ga, Ge:Ga	Mid-infrared detectors on SIRTF, COBE, ISO, IRTS.
Solid-state photomultiplier (SSPM)	Impurity ionization energy	< 28 μm	0.4-0.7	50000	Si:As	Infrared-dead version, called Visible Light Photon Counter (VLPC), used in scintillators at the CDF experiment, Fermi National Laboratory.
Photomultiplier tube	Photoelectric effect (work function)	< 1 μm	0.01-0.1	$10^6 - 10^8$	Na_2KSb:Cs, GaAs:Cs-O, Cs_3Sb	Microchannel plates are arrays of tiny photomultipliers.
Extrinsic photoconductor	Impurity ionization energy	< 200 μm	0.05-0.4	0.1-10	Si:As, Ge:Be, Ge:Ga	Far-infrared detectors on SIRTF, COBE, IRAS, ISO, IRTS.
Superconductor-insulator-superconductor (SIS) tunnel junction	Superconducting energy gap (Cooper pair binding energy)	> 350 μm	0.1-0.25	1	Pb, Nb, NbN	All millimeter-wave and submillimeter observatories use these in their receivers now.
Hot-electron microbolometer	None	All	0.1	---	Nb, NbN	Tiny volume superconducting transition-edge bolometer; very fast detector used in THz-frequency heterodyne receivers.

Device	**Nature of gap**	**Wavelengths covered**	**Typical η**	**Typical *G***	**Materials**	**Examples, comments**
Semiconductor bolometer	None	All	0.5	---	Extrinsic Si, Ge	Tend to be somewhat noisy unless *very* cold. Not a photodetector in any sense.
Photographic emulsion	Molecular electronic transitions	< 1 μm	0.01-0.03	---	Ask Kodak.	Can still cover bigger fields with emulsion than with arrays of photodetectors.
Eyes	Molecular electronic transitions	0.4-0.7 μm	0.1-0.2	---	Rods	Can't average the signals easily.