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 $\eta \leq 1$, 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.

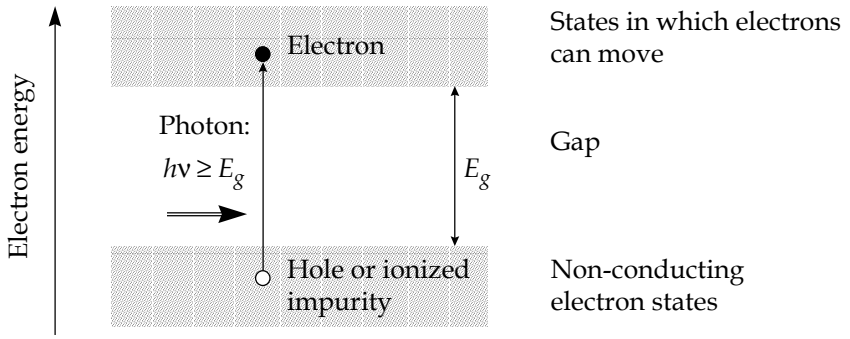

Figure 18.1: schematic diagram of absorption of an incident photon, and production of conduction electron and a hole or ionized impurity, in a photodetector.

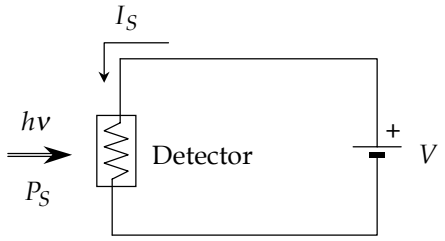

Figure 18.2: incident power P_S in photons of energy $h\nu$, and photocurrent I_S, in a photodetector (represented by a resistor) with *bias* voltage V.

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, and the thermometer measures the temperature increase. It doesn't matter what the light's frequency is in this case; the same amount of energy in photons of two different frequencies would produce the same signal. That's how bolometers work. They are often made in "composite" form, with the absorber and thermometer in good thermal contact but built of different materials. Electronic materials that have large temperature coefficients 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 Summary of 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.

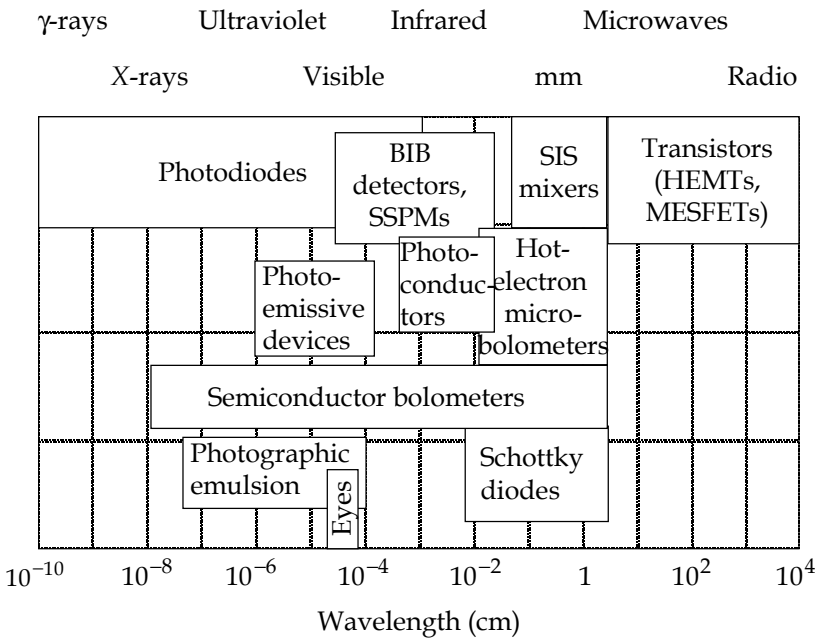

Figure 18.3: modern astronomical detectors and the ranges in wavelength over which they find use.

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.

18.5 Photoemissive devices: phototubes and photomultipliers (optional)

The vacuum phototube is one of the simplest photon-detecting devices. It just consists of two metal electrodes (in vacuum), with a high voltage between them, as in Figure 18.4, and it works by the photoelectric effect: metals can absorb photons and give electrons off into space, with kinetic energy given by

$$K = h\nu - \varphi \quad . \tag{18.3}$$

φ, is called the work function, and is different for different metals, in general. The work function is the threshold of the photoelectric effect: phototubes only respond to light with $h\nu > \varphi$. When an electron is kicked off the cathode, the voltage accelerates it to the anode, and thus one electron makes it throughout the circuit for each absorbed photon (i.e. $G = 1$).

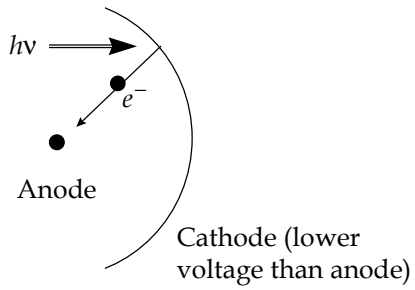

Figure 18.4: vacuum phototube.

Metals, as you are aware, are generally shiny, and good at reflecting light rather than absorbing it. The photocathodes with the highest quantum efficiencies have semiconductor coatings on them and aren't quite as shiny, and the best ones have η = 0.2-0.3; more typically, $\eta < 0.1$.

The smallest work functions are of order 1 eV, so the long wavelength cutoff is generally no greater than 1 μ m. Phototubes are thus mostly useful for visible light detection.

If a high-energy $(K >> \varphi)$ electron hit a metal surface several other electrons will often be kicked out. If these electrons can accelerate to another metal surface, each will kick several more out. Do this many times, making an ever-increasing cascade of secondary electrons, and you can get hundreds of thousands of electrons through the circuit for each absorbed photon. That's the principle of the *photomultiplier,* illustrated in Figure 18.5. Good photomultipliers have $G = 10^5$- 10^6, and can detect the arrival of *single photons*. A closely related device for image-taking is the *microchannel plate*, which is essentially an array of photomultipliers (very tiny ones) made of cylindrical channels etched in a semiconductor wafer.

18.6 Photoconductors (optional)

Photoconductors are the simplest semiconductor detectors of light. In a semiconductor, an electron cannot have an arbitrary combination of energy and crystal momentum. The reason is that the crystal acts as a three-dimensional "diffraction grating" for the electron wavefunctions: for given momenta, there are certain forbidden energies, or energy *gaps*, in the spectrum of electron states. One may think of these gaps as the analogues of the angles between orders of a diffraction grating. The ranges of allowed energies are called *bands*; the lowest energy band is the one for which all the atoms on the lattice have all their original

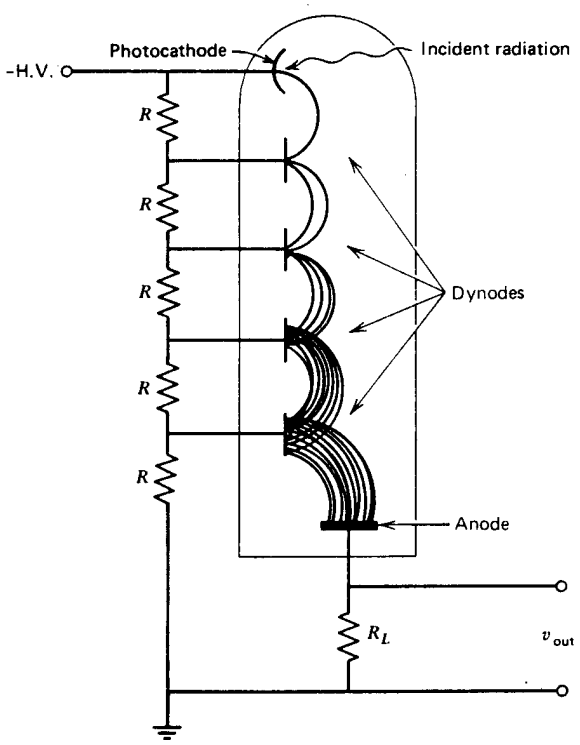

Figure 18.5: schematic diagram of a vacuum-tube photomultiplier (from Boyd, 1983).

electrons bound to them, and is called the *valence band*. Higher energy bands are called conduction bands; usually only the next higher-energy one plays any role, and it's called the conduction band. At low temperatures, with no light shining on the crystal, all the electrons are in the valence band, and none are in the conduction band. The resistance of the crystal in this case is infinite; ideally; no current can flow through it.

Semiconductors that are useful in detection tend to be formed from elements from a small part of the periodic table on either side of the column of *elemental* semiconductors, carbon (in its diamond form), silicon, germanium, and (gray) tin, as shown in Figure 18.6. A list of commonly-used detector semiconductors appears in Table 18.2.

Suppose the forbidden gap is E_g, as in Figure 18.1. A photon with $h\nu \geq E_g$ can be absorbed by the particles in the valence band, resulting in an electron in the conduction band. If the crystal has a voltage on it, as shown above, the electron goes off and becomes part of a current, moving toward the positive-voltage side of the crystal. And not only the electron - the hole it leaves behind can be filled by a neighboring valence-band electron, and so forth; the *hole* propagates in the direction opposite that of the electrons. If the electron and hole both make it to their respective electrodes, that's equivalent to one electron making it all the way through the crystal from one end to the other (i.e. $G = 1$). If the flux of light on the detector is very large, it may be possible for electrons *not* to make it throughout the detector all the way. It could, for instance, encounter a hole and recombine in such a way that the binding energy comes out in some other form other than light (for instance, lattice vibrations: *phonons*). In this case the photoconductive gain is *less* than unity.

	12	13	14	15	16
2		5 B 10.81 $-2s^2 2p^1$	6 C 12.011 $-2s^2 2p^2$	7 N 14.0067 $-2s^2 2p^3$	
3		13 Al 26.9815 $-3s^2 3p^1$	14 Si 28.0855 $-3s^2 3p^2$	15 P 30.9738 $-3s^2 3p^3$	
4		31 Ga 69.72 $-3d^{10} 4s^2 4p^1$	32 Ge 72.59 $-3d^{10} 4s^2 4p^2$	33 As 74.9216 $-3d^{10} 4s^2 4p^3$	34 Se 78.96 $-3d^{10} 4s^2 4p^4$
5	48 Cd 112.41 $-4d^{10} 5s^2$	49 In 114.82 $-4d^{10} 5s^2 5p^1$	50 Sn 118.71 $-4d^{10} 5s^2 5p^2$	51 Sb 121.75 $-4d^{10} 5s^2 5p^3$	52 Te 127.60 $-4d^{10} 5s^2 5p^4$
6	80 Hg 200.59 $-5d^{10} 6s^2$	81 Tl 204.383 $-5d^{10} 6s^2 6p^1$	82 Pb 207.2 $-5d^{10} 6s^2 6p^2$	83 Bi 208.98 $-5d^{10} 6s^2 6p^3$	

Figure 18.6: section of the periodic table of elements relevant for modern semiconductor detectors.

The type of photoconductor discussed above is called an *intrinsic* photoconductor because the semiconductor is an *intrinsic* semiconductor – no impurities, which would provide additional states in the forbidden gap to which electrons or holes could become bound. Semiconductors with deliberately introduced impurities, called *doped* or *extrinsic* semiconductors, also lead to a useful sort of photoconductor. Consider for simplicity an elemental intrinsic semiconductor like silicon or germanium, "doped" with a small concentration (say, a part in 10^7 or 10^8) of an element just to the right of the carbon column in the periodic table (say, phosphorous, to take a concrete example). Faced with trying to fit in the lattice, each impurity atom occupies a lattice spot and makes four bonds to its nearest neighbors, just like host-crystal atoms do, but winds up with an extra electron. Because of the charge on the phosphorous nucleus the electron tends to still be bound to it, but the effect of the other nuclei and electrons in the lattice is to make this binding very weak – the electron is easy to ionize. It is appropriate to think of the extra electron and the remaining unshielded charge on the phosphorous nucleus to comprise a hydrogen-like atom with a peculiarly small ionization potential. Dopants like phosphorous in Si or Ge are called *donors*, because they have one electron to spare after bonding. Material doped with an excess of donors is called *n-type material*. Similarly, impurity atoms to the left of Si and Ge, when occupying a lattice position, try to make four bonds to the nearest neighbors, but come up one electron short. One can say, equivalently, that they have an excess *hole*. This hole is loosely bound to the impurity atom, just like in the donor; one may think of it as an antihydrogen-like atom. Material like this, with an excess of *acceptors*, is called *p*-type.

Extrinsic semiconductor crystals work much like the intrinsic ones as photoconductors. At low temperatures and in the absence of light, all the electrons in the crystal are bound either to an impurity atom or a lattice atom, and it won't conduct electricity. Let light with energy greater than the ionization potential of the donors (or acceptors) get in, through, and electrons (or holes) can be promoted to the conduction (or valence) bands and comprise a current (see Figure 18.7). In this case, though, there's no pair of electron and hole going off in opposite directions; the electron or hole produced in the ionization go off by themselves, and the ionized impurity sits there in its lattice position until another charge carrier gets close enough to it to recombine. Again, that makes it possible for a photon absorption to produce a

carrier that doesn't quite make it all the way through the crystal, but still comprises a current ($G < 1$), or even a carrier that makes it all the way through several times before recombining ($G > 1$). Typically, G lies between 0.1 and 10. The quantum efficiency η can be as high as about 0.7 (without antireflection coatings) for the shorter-wavelength photoconductors, but is usually in the range 0.2 - 0.4.

Table 18.2: pure and lightly-doped semiconductors for detectors.

Material	Gap (eV)	λ_C (μm)
GaP	2.25	0.55
CdTe	1.65	0.75
$Hg_{1-x}Cd_xTe$ *	1.65 to -0.2	>0.75
GaAs	1.4	0.88
Si †	1.1	1.1
Ge †	0.75	1.6
InAs	0.33	3.7
PbTe	0.30	4.1
PbSe	0.27	4.6
InSb	0.23	5.5
Si:In	0.16	8
Si:Ga	0.073	17
Si:Bi	0.069	18
Si:As	0.054	23
Si:Sb	0.041	30
Si:Li	0.031	40
Ge:Be	0.024	52
Ge:Ga	0.0108	115
Ge:Sb	0.0092	135
Stressed Ge:Ga ‡	0.0056	220

* HgTe is a *semimetal*; it has a negative bandgap. Thus in principle $Hg_{1-x}Cd_xTe$ can be "tuned" through zero bandgap ($x \approx 0.15$); in practice, however, the tendency of the component elements to "cluster" prevents this material from responding at very long wavelengths.
† The elemental semiconductors Si and Ge have *indirect* bandgaps; photoresponse at wavelengths near that corresponding to the bandgap must be phonon assisted.
‡ Stressed uniaxially and near the strain limit at low temperatures.

Because of the bandgap in intrinsic photoconductors and the impurity ionization potential in extrinsic ones, these devices each have a long-wavelength threshold for photoresponse. Some of the impurities have very small ionization potentials and thus respond at long infrared wavelengths. Intrinsic photoconductors don't work quite as well as the next type of device we'll consider, photodiodes, and respond over the same wavelength range as photodiodes, so they tend to not get much use. Table 18.2 contains a list of some intrinsic and extrinsic semiconductors frequently used in detectors, with their band gaps or impurity ionization potential and the corresponding threshold wavelength.

For extrinsic photoconductors the energy needed to produce carriers is quite small. Thus these devices usually need to be operated at very low (cryogenic) temperatures, in order that thermal energy (lattice vibrations) cannot produce electrons or holes that one could not tell apart from photo-produced ones. As a rule,

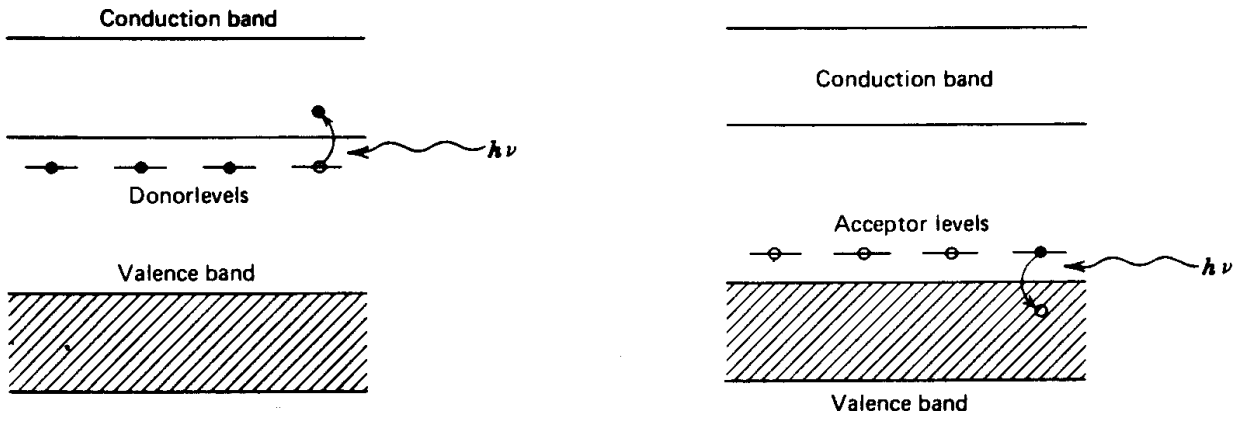

Figure 18.7: extrinsic photoconductors (from Boyd, 1983).

$$T << \frac{E_g}{k} \quad \text{or} \quad \frac{\Delta E_i}{k} \quad , \tag{18.4}$$

where ΔE_i is the energy difference between the ground and first excited state of an impurity. The longer the threshold wavelength, the colder they need to be. Silicon extrinsic PCs generally need to be at T = 4 – 10 K, and germanium PCs like Ge:Ga need to be below 4 K. (Stressed Ge:Ga, for instance, works best at T = 1.3-1.4 K).

18.7 Photodiodes and photovoltaic detectors (optional)

These devices, which include some of the best light detectors of any sort, are based upon *p-n junctions*: a single crystal doped partially with acceptors, partially with donors, with a sharp interface separating the two (Figure 18.8). Remember that in some respects we can think of acceptors as antihydrogen-like, and donors as hydrogen like. What happens when you bring antimatter and matter into contact? They neutralize, of course, and that's what happens here. Some of the acceptors near the interface grab electrons from the donors on the other side, and for a range about the interface no neutral impurities are left. This place where the *p*s and *n*s neutralized each other is called the *space charge,* or *depletion, region*. The width of the depletion region depends upon the densities of the dopants on either side of the interface, as we'll discuss further below.

We said the *p*s and *n*s "neutralize," but in terms of electric charge the depletion region winds up polarized. The acceptors, "accepting" electrons they didn't start with, wind up with a net negative electric charge and leave the donors on the other side with positive charges. This *p-n* junction has a built-in polarization, and consequently a built -in electric field. It either takes work or produces work to move a charge across an electric field region, so the effect of the *p-n* junction on the energies of electrons in the valence and conduction band is as illustrated in Figure 18.9: the bands bend so that one side has higher energies than the other. This effect makes it a useful circuit element whether or not it's detecting light - it's a *diode*. If you put an additional voltage on the crystal, you'll see that the current will flow predominantly in one direction, because the other polarity is opposed by the built-in field. The photodiode structure works as a detector whether or not there's an additional voltage put on it. It's usually used with a reverse bias or zero bias (in the latter condition it's often called a *photovoltaic* detector).

If a photon with energy $h\nu \geq E_g$ is absorbed in the depletion region, an electron - hole pair is produced, and these are swept in opposite directions by the built-in field, as shown in Figure 18.10. These charges

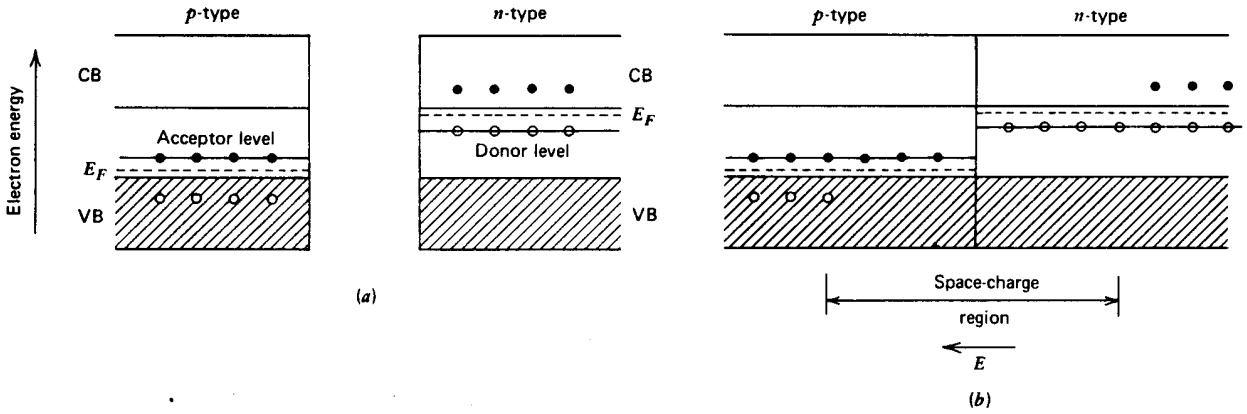

Figure 18.8: (a) Separate crystals of *p*- and *n*-type semiconductor material. (b) A *single* crystal made of the two in frame a, illustrating the depletion region (Boyd, 1983).

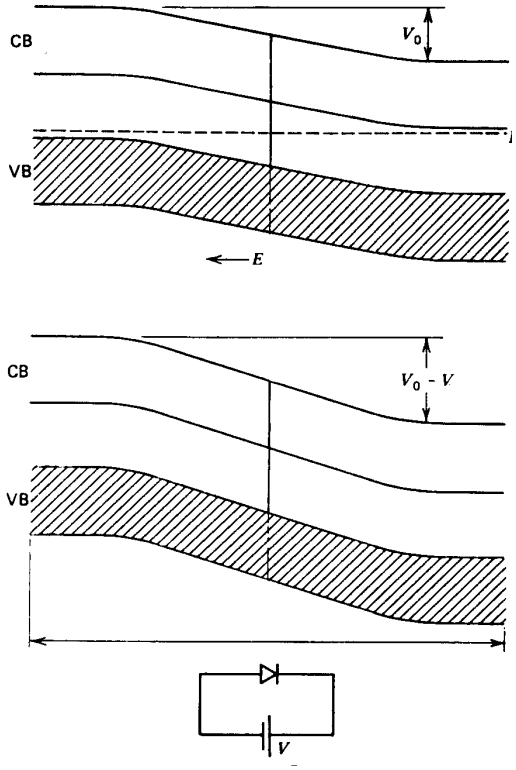

Figure 18.9: electric field and valence and conduction band energies in a *p*-*n* junction (Boyd, 1983).

can be collected at the ends, and the result is that exactly one electric charge made it all the way through the detector ($G \equiv 1$), or

$$I_S = \frac{\eta e P_S}{h\nu} \tag{18.5}$$

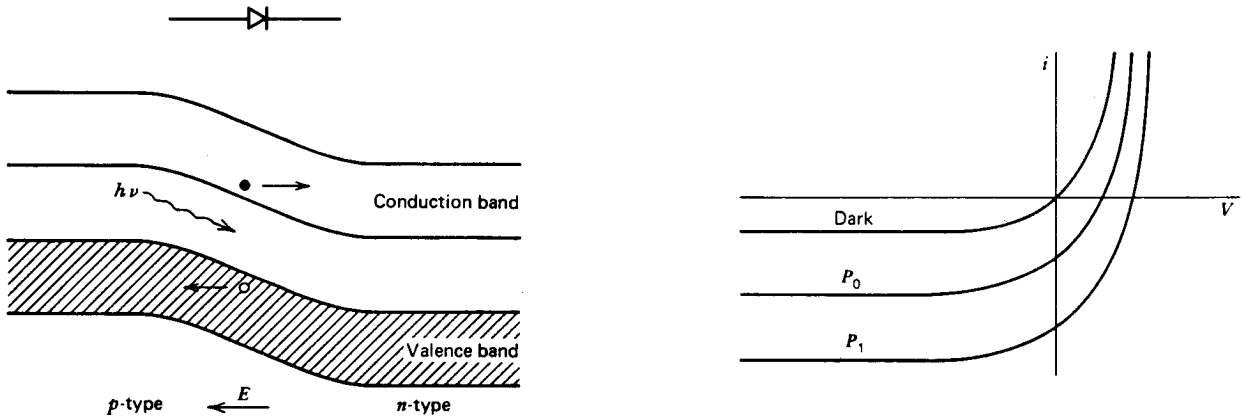

Figure 18.10: detection of light in a semiconductor *p*-*n* junction (left), and current-voltage characteristics (right). (Boyd 1983)

It is a relatively simple exercise in the solution of Poisson's equation to show that the width of the depletion region is

$$w = \sqrt{\frac{2\varepsilon(V_0 - V)}{e}\frac{N_A + N_D}{N_A N_D}} \tag{18.6}$$

where N_A and N_D are the volume densities (number per unit volume) on the *p*- and *n*- sides of acceptors and donors, respectively, ε is the dielectric constant (ε = 11.3 for silicon, 15.4 for germanium), and V_0 is the built-in voltage given by

$$V_0 = \frac{kT}{e}\ln\left(\frac{N_A N_D}{n_i^2}\right), \tag{18.7}$$

where

$$n_i^2 = 4\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} e^{-E_g/kT}, \tag{18.8}$$

and m_e^* and m_h^* are the effective masses of electrons and holes in the crystal. (The latter two equations are not easy to derive, and you won't be held responsible for them). The point of Equation 18.6 is that the depletion-region width is larger, the smaller is N_A and N_D (i.e. in a *very* pure crystal). The world's purest crystals (of *any* sort) are large crystals of germanium with residual impurity concentrations of about $N_A = 10^9$ cm^{-3} and $N_D = 3\times10^8$ cm^{-3} (that is, germanium pure to one part in about 10^{13}!). They can be made into photodiodes with depletion regions as long as 25 cm. Diodes like this, comprised of cylinders about 10 cm in diameter, are the world's most sensitive *gamma-ray detectors* ($h\nu \geq$ a few hundred keV). Depletion-region widths of a few microns are perfectly adequate to absorb visible and infrared light, though, and that's the form in which photodiodes usually appear. It is not uncommon to see photodiode arrays with visible and/or near-infrared quantum efficiencies greater than 0.8. Photodiodes are used whenever possible, for that reason, and are the detectors of choice for $\lambda \leq 5\ \mu$m. Their threshold wavelengths are given in Table 18.2, as they're nearly the same as that obtained from the

intrinsic bandgap. The ones most widely used these days are silicon ($\lambda < 1.1\ \mu$m), GaAs ($\lambda < 0.88\ \mu$m), InAs ($\lambda < 3.7\ \mu$m), InSb ($\lambda < 5.5\ \mu$m), and HgCdTe (adjustable bandgap, but usually $\lambda < 10\ \mu$m).

18.8 Blocked-impurity-band (BIB) detectors (optional)

There's a limit to how heavily one can dope an extrinsic photoconductor and still have it perform well. The more heavily doped it is, the closer together the impurities are, on average, and the more wavefunctions overlap. Appreciable overlap can raise the chances for trapped electrons to *tunnel* from one impurity to another, without needing to be ionized by an incoming photon and thereby get promoted to the conduction or valence band. This tunneling current, called *dark current* because it's there whether or not light is shining on the detector[1], needs to be kept much smaller than any photocurrent in order for the noise associated with dark current not to dominate over other noise sources. Thus the most sensitive extrinsic photoconductors are very lightly doped. However, it takes a certain *total number* of impurities in a detector to absorb an appreciable fraction of the incident light, so if one reduces the density one must increase the detector's volume. For infrared photoconductors made of extrinsic silicon or germanium, it turns out that a 1-10 mm long path through the detector is required for the absorption of most of the light, different materials requiring somewhat different lengths. For several reasons this rather long length turns out to be a severe practical disadvantage. For instance, it makes it extremely difficult to construct high-performance *arrays* out of such semiconductor material. Common focal-plane image sizes are on the order of millimeters, as you will no doubt recall, and thus the detectors' length needs to be comparable to or greater than their widths to absorb all the light. This is bad because it leads to *electrical crosstalk*: in this geometry it's relatively easy (under the influence of the fringing electric field from a neighboring detector's bias voltage) for photocarriers to wander into adjacent detectors and thus not get "counted" in the part of the image they belong to. Another disadvantage of the large size is that it makes them pretty good detectors of gamma-rays, X-rays and high-energy particles (like the γ-ray detectors discussed in the previous section). Usually absorption of a high-energy particle completely swamps the infrared signal. Repeated absorption of high-energy particles can cause long-lived and unstable changes to the detector's responsivity, or even permanent damage to the device. The latter are very serious problems for detectors used on satellites, as many astronomical infrared detectors are.

These and many other nasty optoelectronic problems with photoconductors are not present in a relatively recently-developed take-off on photoconductors, the so-called *blocked-impurity-band (BIB) detector*. The workings of BIB detectors are illustrated in Figure 18.11. The trick is to notice that the dark current in a heavily-doped extrinsic photoconductor involves carriers that hop from impurity site to impurity site without ever making it to the conduction band or valence band. With increasing impurity density this hopping gets easier and easier, and one can think of this as the impurities forming their own band. (This *impurity band* formed by the overlapping impurity states is not really quite the same as the valence or conduction band, but that's a detail that you won't have to address unless you take a solid-state physics course). If one just puts electrodes on impurity-banded material a large dark current flows. However, by adding a *crystal layer of undoped material* before forming the electrodes, one prevents the dark current from making it through the circuit: the undoped material, having no impurities to which to hop, *blocks* the impurity band. Photo-excited carriers *can* make it throughout the circuit, though, because the doped and

---

[1] Besides *tunneling* dark current, there's another form of dark current due to *thermal* generation of carriers: when kT is high enough compared to E_i, lattice vibrations (phonons) can ionize an appreciable fraction of the impurities. This is also to be avoided because the thermal current adds noise. Thermal dark current *can* be "frozen out," though, just by making the detector colder, while tunneling dark current can exist even at zero temperature.

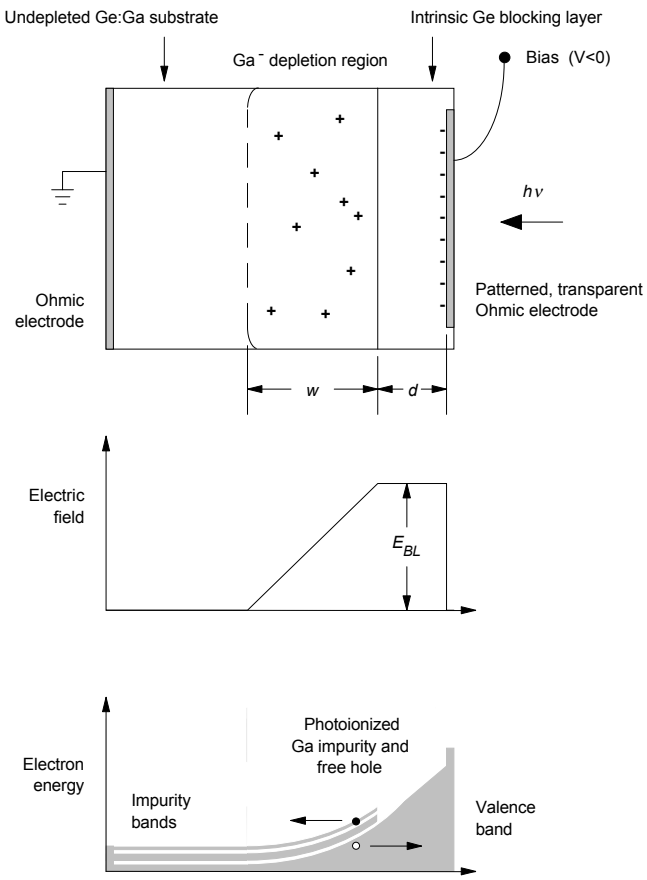

Figure 18.11: structure of a *p*-type BIB detector, not drawn to scale. (a) Charge distribution for negative bias. (b) Electric field distribution for negative bias. (c) Electron energy diagram for negative bias, illustrating the detection process.

undoped material have the same conduction and valence bands. Thus low tunneling dark currents can be achieved for heavily-doped, and therefore small-volume, detectors. The photodetection process goes as follows for a *p*-type BIB detector at small bias voltage. Photoionization of an impurity produces an electron in the impurity band and a hole in the valence band. To distinguish the former from a "real" electron in the conduction band we'll call this an ionized impurity (A^-, since it's an acceptor in this example). If the BIB detector has a voltage on it such that the electrode on the undoped layer is negative with respect to the other one, the hole will move toward this electrode. The ionized impurity can move toward the other electrode by tunneling, and the result is a total of *one* electron through the circuit for each absorbed photon. The only way for tunneling to participate in an observable current is for an ionized impurity to be produced in conjunction with a carrier in the valence or conduction band by a photon. This operation resembles that of a reverse-biased photodiode.

One can press the analogy between BIBs and photodiodes further. Consider again a BIB with a heavily-doped ("absorbing") layer and an undoped ("blocking") layer; initially with no voltage across it. Along with the majority impurity (the acceptor Ga in Figure 18.11), the crystal growth process always introduces some unwanted impurities of the other type, hopefully in a vastly smaller concentration. Each of these *compensating* impurities will annihilate a majority impurity, and in equilibrium at low temperatures there will be equal, small numbers of ionized donors and acceptors. Now consider applying a voltage to the device, with the positive (negative) lead on the blocking layer for *n*-type (*p*-type) absorbing layers. Ionized majority impurities can move in response to the field, because of impurity-band conduction, and are swept out of the device for a certain depth. For a given voltage the depth is determined by the

concentration of compensating impurities: since they're all ionized but fixed in position (*not* impurity banded), they produce their own electric field which opposed the externally applied one. Thus an *ionized-impurity depletion region* is formed in which the electric field increases from zero up to the maximum value that holds for the blocking layer. The depth of this region can be obtained by solution of Poisson's equation:

$$w = \sqrt{\frac{2eV}{N_D} + d^2} - d \quad , \tag{18.9}$$

an expression much like that for a *p-n* junction, Equation 18.6. Photoionization of a neutral impurity in this region leads to one carrier traversing the circuit, but in the absence of light, no current is drawn after the initial sweep-out of the majority ionized impurities This is all just like photodiode, except that the depletion region and the electric field aren't built in - one has to apply an external bias voltage (typically lying in the 0.01 - 3 V range) to make it work.

Another interesting device based on the BIB detector is the *solid-state photomultiplier* (SSPM), which is essentially a BIB with carrier-multiplication gain like a photomultiplier tube. It gets this gain by being engineered to sustain a much higher bias voltage than usual BIBs - 6-10V for present extrinsic silicon devices. Carriers are photoexcited as usual but the electric field is high enough in the region near the blocking layer that they can accelerate to kinetic energies greater than the impurity binding energy in distances less than the carrier mean free path. So they each *collisionally* ionize an impurity, giving two carriers which get quickly accelerated, ionize two more impurities to give four carriers, and so forth until an "avalanche" of impurity-impact-ionized carriers are produced for each initial photoexcited carrier. Present Si:As SSPMs have gains around G = 50,000, enabling a large enough current pulse that single infrared photons can be detected.

BIB detectors have quantum efficiency in the infrared in the 20-60% range, and work at visible wavelengths, too, where Si:As SSPMs have shown $\eta \geq 70\%$ without antireflection coatings. Their long-wavelength thresholds are somewhat greater than that of the corresponding photoconductor (see Table 18.2), owing partially to *impurity-band broadening*. The extent in energy of allowed states in an impurity band turns out to be broader than the original hydrogen-like states, because of the impurity-state overlap, and the edge of the impurity band winds up closer to the conduction or valence band, reducing the effective ionization potential. For instance, Ge:Ga BIBs have $\lambda_c \sim 190\ \mu$m, compared with 115 μm for unstressed Ge:Ga photoconductors.

SSPMs made out of Si:As detect single photons at all wavelengths between 3000 Å and 28 μm at high quantum efficiency, and therefore can be considered one of the world's best light detectors.

Like photoconductors, BIB detectors must be operated at cryogenic temperatures, usually $T \leq 4$ K, to get low dark currents.

18.9 Superconductor-insulator-superconductor (SIS) tunnel junctions

The longest-wavelength photodetector we shall consider is the SIS quasiparticle tunnel junction. This detector is different from the devices we have considered hitherto because it (a) involves superconductors rather than semiconductors; (b) has an *upper* frequency limit but no long-wavelength threshold; (c) generally needs to be made so small compared to the wavelength of light it detects that the light has to be fed to it by antennae rather than simply by focusing free-space-propagating light, like the other detectors.

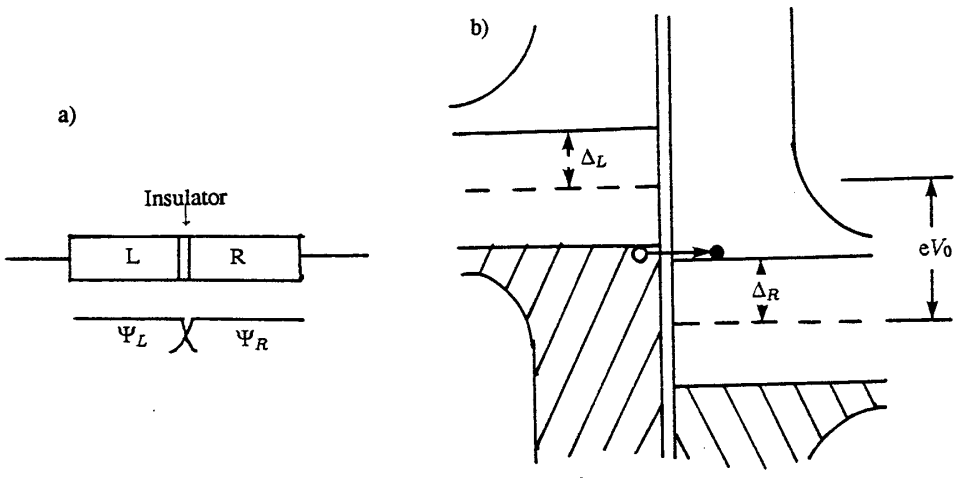

Figure 18.12: SIS tunnel junction. (a) Diagram of structure. (b) Diagram of density of states (horizontal axis) *vs.* quasiparticle energy (vertical axis) for a junction with voltage V_0, and an illustration of the photon-assisted tunneling process. (Wengler 1987)

In some metals at low enough temperature, the interaction of free electrons with the lattice of metal ions results in a net *attraction* between electrons and a binding of electrons into systems called *Cooper pairs*. These pairs have charge -2*e* and spin zero (the electrons, each spin ½, have their spins anti-aligned), and as a result of the latter condition the Pauli exclusion principle is no longer obeyed by the charges in the metal (only half-integer spins obey the Pauli principle). With spin zero, all of the Cooper pairs are allowed to be in the same state, and this is in fact what happens in the transition to the superconducting state - all of the pairs "condense" into the minimum - energy state. The extent of this state can be many orders of magnitude larger than the inter-atomic spacing. This and the fact that the Cooper pairs are all in the same state and are identical particles, means that a current can flow in the metal via quantum-mechanical exchange, without adding any energy to the carriers, and without resistance. Currents made up of Cooper pairs are called *supercurrents*, and the resistance-free propagation of current in this fashion is the outstanding feature of superconductivity.

Cooper pairs can be broken by adding energy to them. It is useful to think about this in a semiconductor-band sort of way, with a forbidden gap separating the states allowed for the electrons that result from breaking a pair, because of the peculiar energy-momentum distribution of electrons that result from breaking a pair. In this manner we imagine absorption of a photon to lead to the production of a "conduction-like" electron and a "valence-like "one, as in a semiconductor, except that this time the charge of the "hole" is the same as that of the "electron." Photons of energy greater than the superconductor's pair binding energy, $E_g = 2\Delta$, can break a Cooper pair. Because and unusual distribution of energy and momentum results, these electrons and holes are referred to as "quasiparticle excitations" instead of "electrons and holes."

The utility of this picture arises in consideration of a device that consists of two superconductors separated by an insulating layer that is very thin (≤ 20 Å) compared to the wavefunction extent ("coherence length"), as in Figure 18.12. With zero voltage across the device, the pair energy E_F is the same on both sides and pairs can tunnel freely. At finite voltage, the pair current (supercurrent) drops to zero because of the energy mismatch, until the voltage difference exceeds the *gap voltage*, $2\Delta/e$ At larger voltages, "valence band" quasiparticles can tunnel into the "conduction band" on the other side of the barrier. Thus the current-voltage curve should look like the lowest curve in the upper panel of Figure 18.13. Ideally, no current flows for voltages less than $2\Delta/e$, but above this voltage the device abruptly starts acting like a resistor.

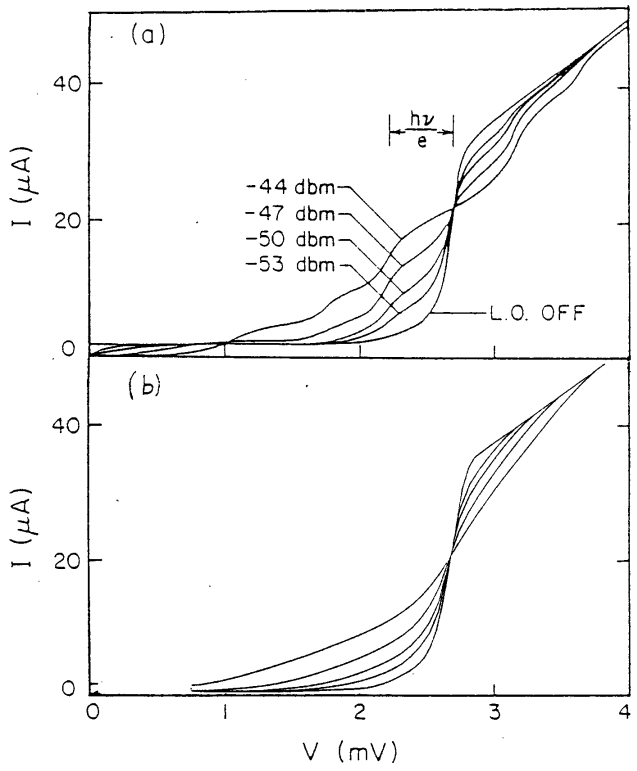

Figure 18.13: current-voltage characteristics of an SIS tunnel junction under varying illumination (upper plot) and temperature (lower plot). Note the steps, spaced by $h\nu/e$, in the *I-V* curves for the illuminated junction, which indicate photon-assisted tunneling. (Wengler 1987)

Since the current is formally zero for this $0 \le V < 2\Delta/e$, a way of making a photodetector out of a tunnel junction suggests itself. For a junction with voltage δ/e *below* the gap voltage, no current flows in the dark, but absorption of photons with energy $h\nu \ge \delta$ would allow a quasiparticle to tunnel to the other side. This is just like any other photodetector with a photoconductive gain of 1; the quasiparticle photocurrent obeys $I = \eta e P_S / h\nu$ The photon-detecting properties can be illustrated graphically by shining monochromatic radiation on a junction and measuring the current-voltage curve, as in Figure 18.13: *steps* appear, due to this *photon-assisted tunneling*. Steps to either side of the gap voltage represent *single* -photon-assisted tunneling; the next steps involve simultaneous absorption of *two* photons and then tunneling, and so forth:

In order to avoid having the capacitance of the junction (impedance $1/i\omega C$; very small at high frequency) short out the radiation, one must make the total area of the junction very small. For millimeter and submillimeter wavelengths, typical sizes are $1\mu\text{m} \times 1\mu\text{m}$. Since this is so much smaller than the wavelengths at which they're applied, diffraction keeps one from using lenses and mirrors and focusing to get the light into the junction. Instead, one has to provide the junction with an antenna to conduct the radiation field to the junction, and to match the telescope's beam to the junction's antenna by use of additional lenses and mirrors. Since an antenna is used, SIS junction detectors can be used with beams no bigger than the diffraction- limited size. (Remember, all antennas have $A\Omega = \lambda^2$.) The antennas are usually made simply by extending the superconducting metal pieces that make up the device out into the pattern of an antenna.

From the *I-V* curves in Figure 18.13, one can see that the SIS junction works well up to photon energies of $h\nu = 2\Delta$ - that is, a "step" that goes all the way from zero bias to the turn-on point. At higher energies it still detects, but the photocurrent starts to decrease for the same incident photon rate because it's just as easy for a high-energy photon ($h\nu >> 2\Delta$) to assist tunneling in one direction as the other; and if current is going in both directions in equal amounts, the result is no net current. SIS detectors don't work at all well for frequencies greater than $\nu = 4\Delta / h$. They do, however, work down to quite low frequencies. Thus SIS junctions have an *upper* frequency cut-off rather than a lower -frequency one - the opposite situation holds for semiconductor and photoelectric devices. The best SIS junctions have quantum efficiency in the 20-30% range. They tend to have far too much dark current to compete with bolometers as detectors of broad-band radiation but work very well as mixers in heterodyne receivers, as we shall see below (section 22).

18.10 Other sorts of astronomical photodetectors

The photodetectors discussed above are special, in that they turn out to be (a) the most sensitive detectors for their particular wavebands and (b) so sensitive, in fact, that they should allow the construction of instruments on all of the observatories in the foreseeable future that are limited in sensitivity only by quantum mechanics or the fluctuation in the natural background radiation from the sky. Not all detectors can do this! Many other detectors, for reasons of particularity or principle, wind up being limited by internal sources of noise, Johnson noise, *etc.*, or are restricted in their choices of integration time or possible format (*vis-a-vis* arrays). Briefly, here are some of them that have been used by astronomers. You still see many of them around, but their use is declining and you might see them disappear from the astronomical scene in the next few years. Starting at short wavelengths (and not trying to be terribly complete):

Geiger counters; proportional counters: Useful at *X*-ray and γ -ray wavelengths, these devices work by having a high-voltage electrode pair in a tube full of easily-ionized gas. When a γ -ray passes through the tube, it can ionize some of the gas, and this ionization leaves a conducting path the gas, briefly, that can draw a current pulse from the high-voltage supply. Just hook an ammeter up to it, and you're done. They don't have very good quantum efficiency or energy resolution, and are being supplanted by semiconductor detectors.

Eyes: Rods are actually pretty good detectors ($\eta >$ 10-20%) but are fairly sparsely spread on the retina. Cones aren't quite as good ($\eta \leq 1\%$). One also can't average signals from one's eyes for very long - the effective integration time is about 1/20 sec. Still, important astronomy was still being done with them as late as the 1930s.

Photographic emulsion: The effective quantum efficiency isn't great (η ~1-3%), it doesn't lend itself to electronic processing very easily, and it suffers from limitations on linearity ("reciprocity failure") and dynamic range, but the plates can be made as large as desired, so they still offer more detail (by far) than the biggest photodiode-CCD arrays. For example, the Palomar Sky Survey plates (14" square) have faint stellar images on them as small as 0.001 inch, so a detector array would need at least 14000 × 14000 detectors to catch up. The biggest photodiode-CCD arrays are currently 4096 × 4096.

