gain. Now consider the case when the signal and pump travel in opposite directions. To keep things simple, suppose that the pump power varies between two states: high and low. As the signal propagates through the fiber, whenever it overlaps with the pump signal in the high power state, it sees a high gain. When it overlaps with the pump signal in the low power state, it sees a lower gain. If the pump fluctuations are relatively fast compared to the propagation time of the signal across the fiber, the gain variations average out, and by the time the signal exits the fiber, it has seen a constant gain.

Another major concern with Raman amplifiers is crosstalk between the WDM signals due to Raman amplification. A modulated signal at a particular wavelength depletes the pump power, effectively imposing the same modulation on the pump signal. This modulation on the pump then affects the gain seen by the next wavelength, effectively appearing as crosstalk on that wavelength. Again, having the pump propagate in the opposite direction to the signal dramatically reduces this effect. For these reasons, most Raman amplifiers use a counterpropagating pump geometry.

Another source of noise is due to the back-reflections of the pump signal caused by Rayleigh scattering in the fiber. Spontaneous emission noise is relatively low in Raman amplifiers. This is usually the dominant source of noise because, by careful design, we can eliminate most of the other noise sources.

3.4.5 Semiconductor Optical Amplifiers

Semiconductor optical amplifiers (SOAs) actually preceded EDFAs, although we will see that they are not as good as EDFAs for use as amplifiers. However, they are finding other applications in switches and wavelength converter devices. Moreover, the understanding of SOAs is key to the understanding of semiconductor lasers, the most widely used transmitters today.

Figure 3.39 shows the block diagram of a semiconductor optical amplifier. The SOA is essentially a *pn*-junction. As we will explain shortly, the depletion layer that is formed at the junction acts as the *active region*. Light is amplified through stimulated emission when it propagates through the active region. For an amplifier, the two ends of the active region are given an antireflection (AR) coating to eliminate ripples in the amplifier gain as a function of wavelength. Alternatively, the facets may also be angled slightly to reduce the reflection. In the case of a semiconductor laser, there would be no AR coating.

SOAs differ from EDFAs in the manner in which population inversion is achieved. First, the populations are not those of ions in various energy states but of *carriers—electrons* or *holes*—in a semiconductor material. Holes can also be thought of as charge carriers similar to electrons except that they have a positive charge. A semiconductor consists of two bands of electron energy levels: a band of

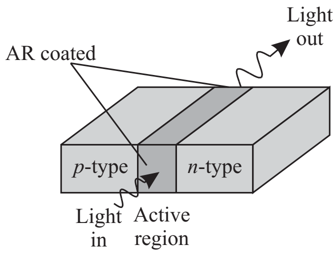

Figure 3.39 Block diagram of a semiconductor optical amplifier. Amplification occurs when light propagates through the active region. The facets are given an antireflective coating to prevent undesirable reflections, which cause ripple in the amplifier gain.

low-mobility levels called the *valence band* and a band of high-mobility levels called the *conduction band*. These bands are separated by an energy difference called the *bandgap* and denoted by E_g. No energy levels exist in the bandgap. Consider a p-type semiconductor material. At thermal equilibrium, there is only a very small concentration of electrons in the conduction band of the material, as shown in Figure 3.40(a). With reference to the previous discussion of EDFAs, it is convenient to think of the conduction band as the higher energy band E_2, and the valence band as the lower energy band E_1. The terms *higher* and *lower* refer to the electron energy in these bands. (Note that if we were considering an n-type semiconductor, we would be considering hole energies rather than electron energies, the conduction band would be the lower energy band E_1, and the valence band, the higher energy band E_2.) In the population inversion condition, the electron concentration in the conduction band is much higher, as shown in Figure 3.40(b). This increased concentration is such that, in the presence of an optical signal, there are more electrons transiting from the conduction band to the valence band by the process of stimulated emission than there are electrons transiting from the valence band to the conduction band by the process of absorption. In fact, for SOAs, this condition must be used as the defining one for population inversion, or optical gain.

Population inversion in an SOA is achieved by forward-biasing a pn-junction. A *pn-junction* consists of two semiconductors: a p-type semiconductor that is doped with suitable impurity atoms so as to have an excess concentration of holes, and an n-type semiconductor that has an excess concentration of electrons. When the two semiconductors are in juxtaposition, as in Figure 3.41(a), holes diffuse from the p-type semiconductor to the n-type semiconductor, and electrons diffuse from the n-type semiconductor to the p-type semiconductor. This creates a region with net negative charge in the p-type semiconductor and a region with net positive

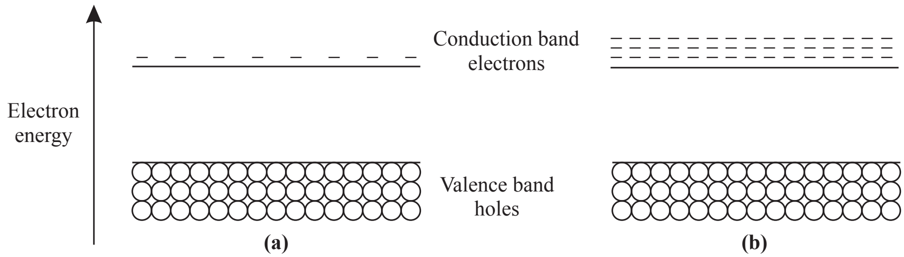

Figure 3.40 The energy bands in a p-type semiconductor and the electron concentration at (a) thermal equilibrium and (b) population inversion.

charge in the n-type semiconductor, as shown in Figure 3.41(b). These regions are devoid of free charge carriers and are together termed the *depletion region*. When no voltage (bias) is applied to the pn-junction, the minority carrier concentrations (electrons in the p-type region and holes in the n-type region) remain at their thermal equilibrium values. When the junction is *forward biased*—positive bias is applied to the p-type and negative bias to the n-type—as shown in Figure 3.41(c), the width of the depletion region is reduced, and there is a drift of electrons from the n-type region to the p-type region. This drift increases the electron concentration in the conduction band of the p-type region. Similarly, there is a drift of holes from the p-type to the n-type region that increases the hole concentration in the valence band of the n-type region. When the forward-bias voltage is sufficiently high, these increased minority carrier concentrations result in population inversion, and the pn-junction acts as an optical amplifier.

In practice, a simple pn-junction is not used, but a thin layer of a different semiconductor material is sandwiched between the p-type and n-type regions. Such a device is called a *heterostructure*. This semiconductor material then forms the *active region* or *layer*. The material used for the active layer has a slightly smaller bandgap and a higher refractive index than the surrounding p-type and n-type regions. The smaller bandgap helps to confine the carriers injected into the active region (electrons from the n-type region and holes from the p-type region). The larger refractive index helps to confine the light during amplification since the structure now forms a dielectric waveguide (see Section 2.3.4).

In semiconductor optical amplifiers, the population inversion condition (stimulated emission exceeds absorption) must be evaluated as a function of optical frequency or wavelength. Consider an optical frequency f_c such that $hf_c > E_g$, where E_g is the bandgap of the semiconductor material. The lowest optical frequency (or largest wavelength) that can be amplified corresponds to this bandgap. As the

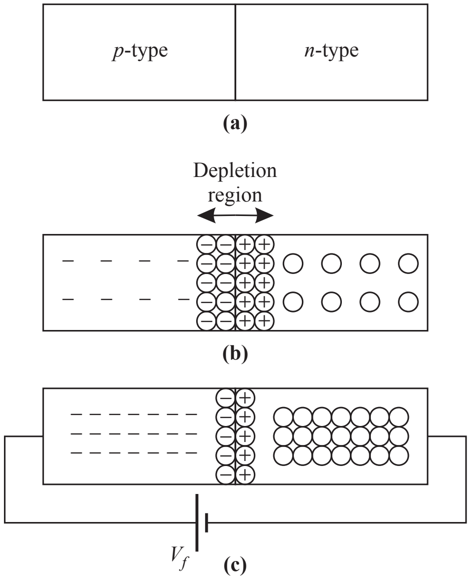

Figure 3.41 A forward-biased *pn*-junction used as an amplifier. (a) A *pn*-junction. (b) Minority carrier concentrations and depletion region with no bias voltage applied. (c) Minority carrier concentrations and depletion region with a forward-bias voltage, V_f.

forward-bias voltage is increased, the population inversion condition for this wavelength is reached first. As the forward bias voltage increases further, the electrons injected into the *p*-type region occupy progressively higher energy levels, and signals with smaller wavelengths can be amplified. In practice, bandwidths on the order of 100 nm can be achieved with SOAs. This is much larger than what is achievable with EDFAs. Signals in the 1.3 and 1.55 μm bands can even be simultaneously amplified using SOAs. Nevertheless, EDFAs are widely preferred to SOAs for several reasons. The main reason is that SOAs introduce severe crosstalk when they are used in WDM systems. This is discussed next. The gains and output powers achievable with EDFAs are higher. The coupling losses and the polarization-dependent losses are also lower with EDFAs since the amplifier is also a fiber. Due to the higher input coupling loss, SOAs have higher *noise figures* relative to EDFAs. (We will discuss noise figure in Section 4.4.5. For our purposes here, we can think of it as a measure of the noise introduced by the amplifier.) Finally, the SOA requires very high-quality antireflective coatings on its facets (reflectivity of less than 10^{-4}), which is not easy to achieve. Higher values of reflectivity create ripples in the gain spectrum and cause gain variations due to temperature fluctuations. (Think of this device as a Fabry-Perot filter with very poor reflectivity, and the spectrum as similar to the one plotted in Figure 3.17 for the case of poor reflectivity.) Alternatively, the SOA facets can be angled to obtain the desired reflectivities, at the cost of an increased polarization dependence.

3.4.6 Crosstalk in SOAs

Consider an SOA to which is input the sum of two optical signals at different wavelengths. Assume that both wavelengths are within the bandwidth of the SOA. The presence of one signal will deplete the minority carrier concentration by the stimulated emission process so that the population inversion seen by the other signal is reduced. Thus the other signal will not be amplified to the same extent and, if the minority carrier concentrations are not very large, may even be absorbed! (Recall that if the population inversion condition is not achieved, there is net absorption of the signal.) Thus, for WDM networks, the gain seen by the signal in one channel varies with the presence or absence of signals in the other channels. This phenomenon is called *crosstalk*, and it has a detrimental effect on system performance.

This crosstalk phenomenon depends on the spontaneous emission lifetime from the high-energy to the low-energy state. If the lifetime is large enough compared to the rate of fluctuations of power in the input signals, the electrons cannot make the transition from the high-energy state to the lower-energy state in response to these fluctuations. Thus there is no crosstalk whatsoever. In the case of SOAs, this lifetime is on the order of nanoseconds. Thus the electrons can easily respond to fluctuations in power of signals modulated at gigabit/second rates, resulting in a major system impairment due to crosstalk. In contrast, the spontaneous emission lifetime in an EDFA is about 10 ms. Thus crosstalk is introduced only if the modulation rates of the input signals are less than a few kilohertz, which is not usually the case. Thus EDFAs are better suited for use in WDM systems than SOAs.

There are several ways of reducing the crosstalk introduced by SOAs. One way is to operate the amplifier in the small signal region where the gain is relatively independent of the input power of the signal. Another is to *clamp* the gain of the amplifier using a variety of techniques, so that even at high signal powers, its gain remains relatively constant, independent of the input signal. Also, if a sufficiently large number of signals at different wavelengths are present, although each signal varies in power, the total signal power into the amplifier can remain fairly constant.

The crosstalk effect is not without its uses. We will see in Section 3.8.2 that it can be used to make a *wavelength converter.*