11.2 ANALOG AND DIGITAL MODULATION

Modulation is the process by which the waveform of a high-frequency carrier wave is modified suitably to transmit information. Usually, the information signal, at a much lower frequency, is impressed on the high-frequency carrier wave. As originally classified, two basic types of modulation were identified, according to the final shape of the carrier waveform: *continuous wave* (cw), in which the carrier is usually a sinusoidal waveform, and *pulse modulation,* in which the carrier is a periodic stream of pulses. Modulation is best described as a frequency translation process in which the information signal is shifted to higher frequencies. More recently, the modulation process has been classified as *analog* or *digital.* In analog modulation the information signal or wave varies the light from the source, or the high-frequency signal, in a continuous manner. Thus, both could be sinusoidal, as shown in Fig. 11.4(a). There is always a one-to-one correspondence between the information signal and the magnitude of the modulated carrier. In digital modulation, discrete changes (on-off) in the intensity of the carrier are

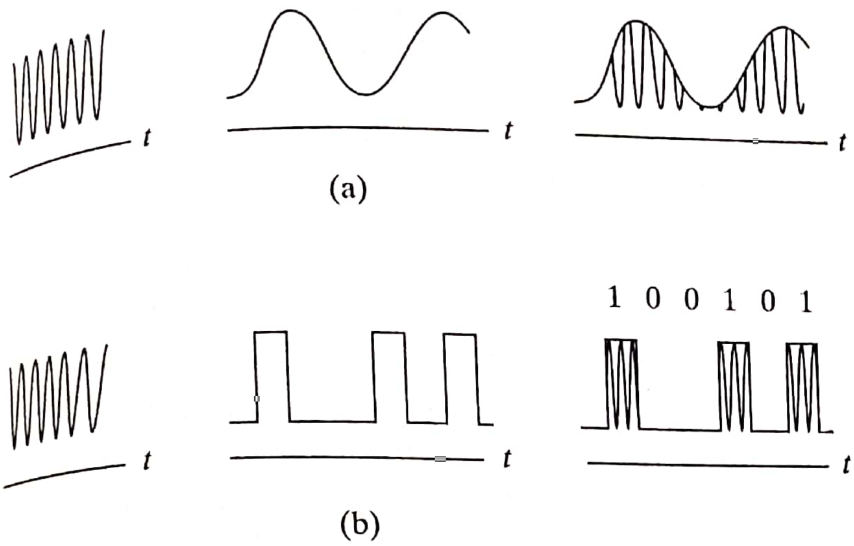

Figure 11.4
(a) Analog and (b) digital modulation of a high-frequency carrier signal.

caused by the information signal. Information is then transmitted by the high-frequency signal as a series of discrete pulses (0 and 1), as shown in Fig. 11.4(b).

Though simpler in concept and implementation, analog modulation suffers from a few practical drawbacks. It requires a higher signal-to-noise ratio at the receiver or detector. For large bandwidth applications the laser is driven at high-current levels, at which the light-current characteristics are very nonlinear. Analog modulation may be more suited for low modulation frequencies. Digital modulation is more suited for large bandwidth optical transmission and reception.

Having described the basic forms of modulation, it is important to mention at this point that the devices to be described in this chapter are basically amplitude and phase modulators, which can be used as external modulators in both digital and analog modulation schemes. In this scheme of modulation the cw light from the source is incident on the modulator in which the signal is impressed through the bias circuit. The output of the device is modulated light.

11.6 OPTICAL SWITCHING AND LOGIC DEVICES

11.6.1 Introduction

Interest in "optical computing" has been around for a few decades and has gone through crests and troughs. Optical computing using lenses and Fourier transforms has been demonstrated. However, versatile optical computers that can replace, or even effectively compete with, electronic computers remain elusive. Some demonstrations of optic logic, utilizing the nonlinear effects in multi-quantum wells, have been made. However, these schemes run into problems, since enormous amounts of switching energy are required and heat dissipation becomes an important issue when arrays of such devices on a single wafer are considered for computing applications. There is a need for low-power photonic switching devices, which can be used effectively for computing and logic applications. In this respect, devices based on the QCSE seem to hold promise. This effect allows one to tailor the device response suitably for the demonstration of simple, optically controlled switching and logic devices, which are next described.

11.6.2 Self-Electro-Optic Device

In addition to QCSE, it is important to understand the photocurrent behavior of the p-i(MQW)-n diode described in Sec. 11.4. Since the QCSE involves a quadratic Stark effect, large electric fields are necessary for any useful shift of the absorption edge (e.g., $E \sim 70$ kV/cm is needed for a 15 meV shift of the heavy-hole peak in a 1 μm GaAs/AlGaAs MQW with 100 Å wells). At the correspondingly large bias values, the MQW diode

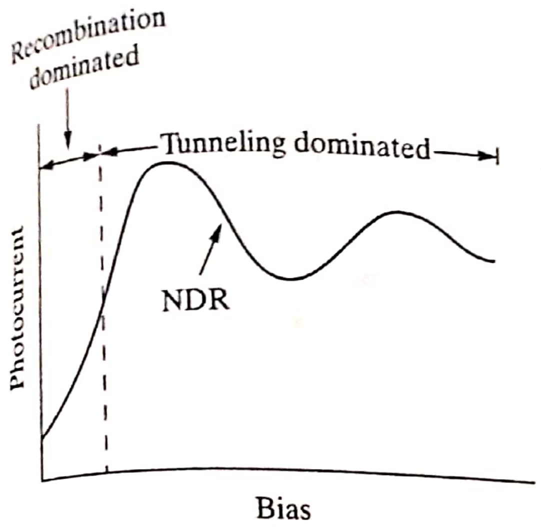

Figure 11.15
Photocurrent-voltage characteristics of p-i(MQW)-n diode.

also behaves as an optical detector. Figure 11.15 shows a schematic of the photocurrent response of a p-i(MQW)-n structure as a function of applied bias. Optical detection in a MQW involves (a) absorption of the incident photons, (b) recombination of some of the photoexcited electron-hole pairs, and (c) tunneling and thermionic emission of electrons and holes through the barriers in opposite directions and their collection at the contact regions to generate an external photocurrent. At low fields, the tunneling rate is small and the recombination process dominates, resulting in a very small photocurrent. At higher fields, the tunneling rate is enhanced and the photocurrent follows the absorption spectra of the MQW. Under these conditions, the photocurrent is given by Eqs. 8.47 and 8.48. Assuming a uniform carrier generation rate G, the photocurrent is given by

$$I_{ph} = \frac{qP_{inc}\alpha(V)W}{h\nu} \tag{11.37}$$

where V is the applied bias, $h\nu$ is the incident photon energy. P_{inc} is the incident optical power (it is assumed that there is no reflection on the top surface and $\eta_i = 1$) and W is the width of the MQW region. It is easy to see that the bias dependence of the photocurrent follows that of the absorption coefficient. The internal quantum efficiency of a MQW structure has been shown to be approximately unity at fields above 10 kV/cm at room temperature. The simultaneous role of an optical detector and a modulator is a unique electro-optic property of an MQW structure. At appropriate wavelengths, a strong negative differential resistance (NDR) region is observed in the photocurrent versus bias voltage relationship of a p-i(MQW)-n structure. This arises because the photocurrent results from the change in absorption coefficient of the MQW due to QCSE. The NDR occurs where the heavy-hole (HH) and the light-hole (LH) peaks cross the photon energy of the input light. As long as the electron and hole densities in the quantum wells are less than 10^{11} cm^{-2}, the absorption process is essentially linear. It may be noted that the photocurrent-voltage (and transmission-voltage) characteristics depend on the relative values of the

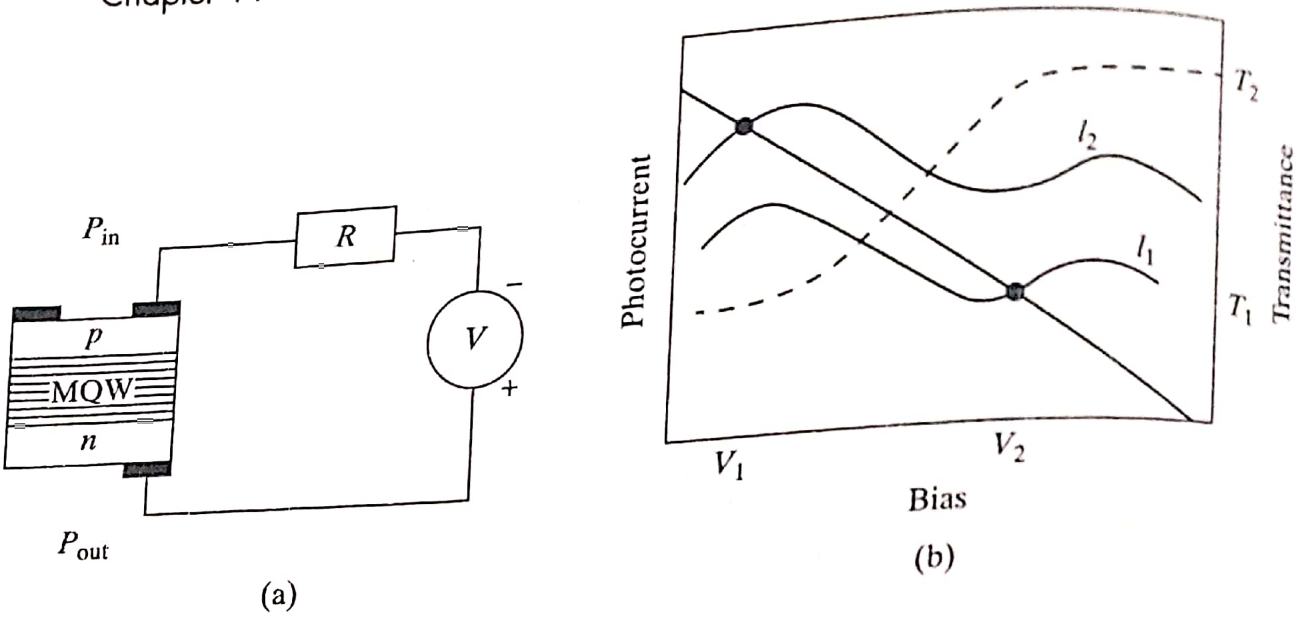

Figure 11.16
(a) SEED circuit with feedback resistor and (b) its excitonic switching property.

photon energy and the exciton resonance energy. By changing the photon energy, the current-voltage characteristics can be modified and the NDR region may be altogether eliminated. As we shall see in the following, this tailorability can be exploited in a number of optically controlled devices.

The potential of the negative resistance region of the photocurrent-voltage characteristics has been exploited to develop a number of photonic switching and logic devices. The first and most important of these is called the Self-Electro-optic Effect Device (SEED).† This device exhibits photonic switching, bistability, and optically induced oscillations due to the negative differential resistance in the photocurrent. The basic SEED circuit with a series resistor is shown in Fig. 11.16(a). The switching action is demonstrated in Fig. 11.16(b). When the light intensity changes from s_2 to s_1, the voltage across the device shifts from V_1 to V_2, causing a transmittance change from T_1 to T_2. Note that this large voltage change, with respect to the optical power change, cannot be achieved without using MQW excitonic transitions. Another important point to note is that the transmission through the device is also changed by almost a factor of two at the same time. Therefore, the device provides an integrating and thresholding capability.

The general principle of the SEED is that the photocurrent flowing through the circuit, including the series resistor, changes the voltage across the modulator, which in turn influences its absorption and transmission. As a consequence the photocurrent is changed. The photonic switching operation is understood in terms of the characteristics shown in Fig. 11.17. Light of energy lower than the HH resonance in the absorption spectrum is incident on the device. Since the diode is typically reverse-biased, the HH peak is red-shifted to lower energies, and most of the light can be transmitted if its energy coincides with the low absorption region between the

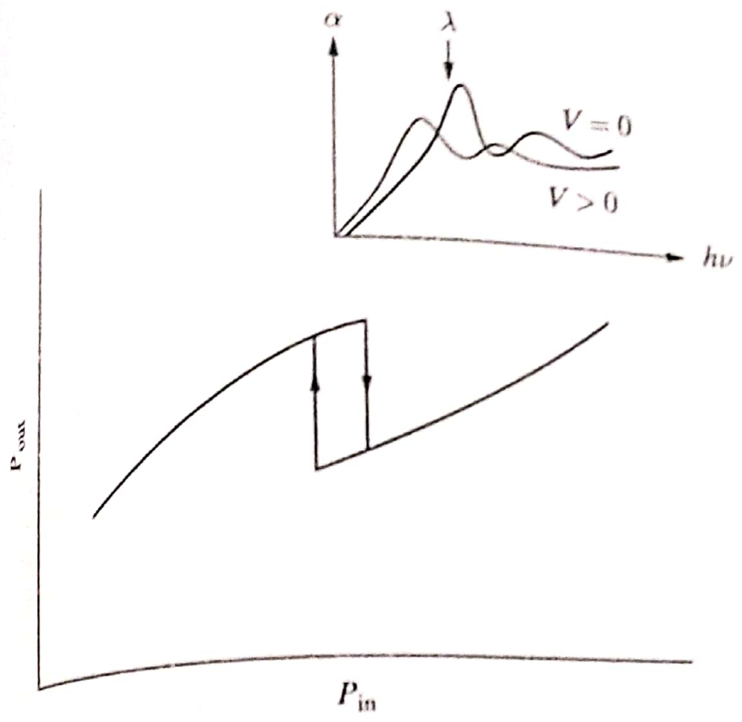

Figure 11.17
Schematic illustration of photonic switching characteristics. The inset shows the light energy with respect to the heavy-hole exciton peak.

HH and LH resonances. Therefore, for low-input power, most of the light is transmitted and the output power increases in proportion to the input power. As the light intensity increases, the photocurrent increases and the voltage drop across the series resistor will increase. Since the bias voltage remains constant, the reverse bias across the diode decreases, which shifts the HH absorption peak to higher energies and the transmission drops. As the input power increases further, the output power will increase again. Thus, the state of the device is altered solely by light intensity. Such photonic switching can also be illustrated with two beams, one for transmission and one for control. The hysteresis observed in the characteristics of Fig. 11.17 is due to the asymmetric shape of the absorption resonances. The feedback due to the resistor is truly opto-electronic.

11.6.3 The Bipolar Controller-Modulator

In the SEED, the path and effects of the signal and control beam are the same and are therefore indistinguishable in their internal effects. Furthermore, in order to make the SEED more compatible with the optical power levels available in optoelectronic integrated circuit (OEIC) technology, it is important to have gain in the circuit. Gain is also essential for larger tolerance in the devices as well as large fan-out and cascadability. One scheme that can be implemented to achieve gain is to connect a bipolar phototransistor in series with the SEED. The control or switching beam is incident on the transistor, while the signal is incident upon and transmitted through the SEED, which functions as the modulator. However, due to the requirement of current continuity the modulator current needs to be high, since the transistor current is usually quite high. This can only be achieved by using the p-i(MQW)-n modulator in waveguide form.

Gain can also be realized by using a heterojunction bipolar transistor (HBT) with a MQW in the base-collector region. This device provides a number of advantages. Since a transistor operates vertically, a large uniform transverse electric field can be applied to the collector-base junction to cause the QCSE. The base terminal provides extra controllability for efficient optical and electronic coupling. Incorporation of the MQW in the collector region effectively allows the realization of a p^+-i(MQW)-n^+ modulator by selective etching of the emitter and so the control signal on the HBT and the information signal (to be modulated) on the modulator can be physically separated. More importantly, the entire structure of the n-p^+-i(MQW)-n^+ MQW-HBT and the p^+-i(MQW)-n^+ modulator can be realized by single-step epitaxy. The schematic of the integrated MQW-HBT along with its equivalent circuit are shown in Fig. 11.18. The transistor amplifies the photocurrent generated in the MQW and provides a voltage feedback to the MQW-HBT by changing its collector-base voltage. The modulator and controller are connected in parallel, and the load is connected in series with the controller and the modulator. The signals detected in both the controller and the modulator give a feedback to themselves via the load, and the absorption of light in both the controller and the modulator is altered. The parallel connection of the controller and the modulator allows the sum of the input signals in these devices to control the modulation of light. It is conceivable that the p-i-n structure could also form a laser, which would become important in the design of OEICs to be discussed in the next chapter. The structure is therefore very compatible with OEIC applications. An important point to realize is that amplification of the photocurrent by transistor action allows low-power photonic switching.

Figures 11.19(a) and (b) show the measured output characteristics for two different switching conditions. In the figures the load lines are also shown. Figure 11.19(a) shows the collector current for different values of optical power at zero base current while Fig. 11.19(b) shows the results for different base currents at fixed optical power. Thus, efficient switching can be carried out by optical or electronic signals. The important point to realize is the presence of amplification of photocurrent, which provides for higher

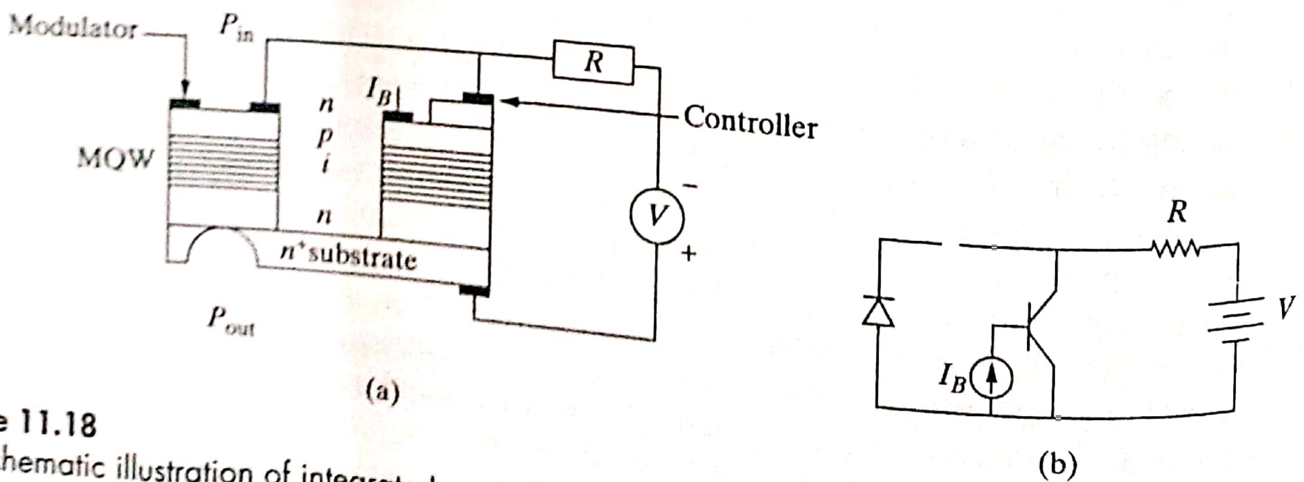

Figure 11.18
(a) Schematic illustration of integrated controller-modulator and (b) its equivalent circuit.

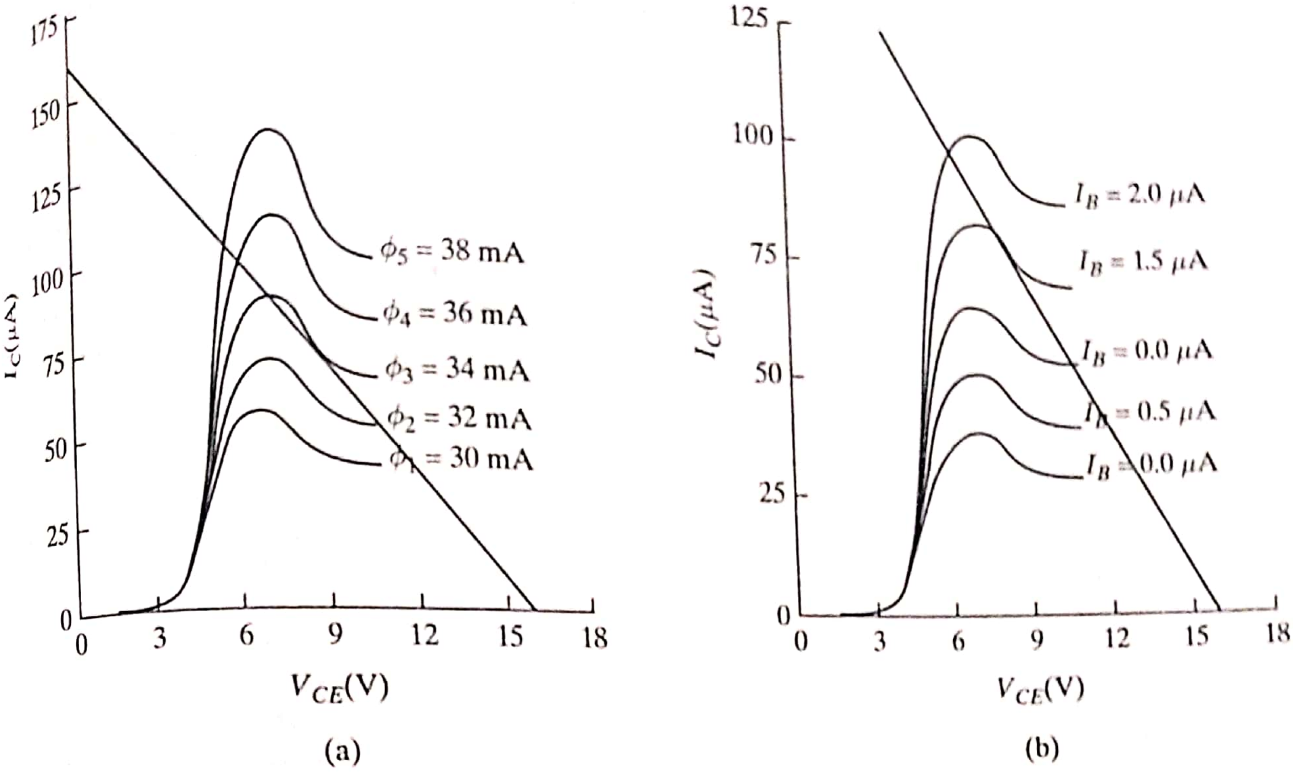

Figure 11.19
Collector current versus collector-emitter voltage characteristic of GaAs/AlGaAs MQW-HBT; (a) at $I_B = 0\ \mu A$, for different illumination levels. The illumination (ϕ) is indicated by the diode laser drive current in mA; and (b) for different base bias at constant illumination ($\phi = 27$ mA). The measurements have been made by the author and co-workers (S. Goswami, *A Quantum Well Phototransistor for Switching Applications*, Ph.D. thesis, University of Michigan, 1992).

sensitivity to light and reduced load resistance. Another point is that the I–V curves can be shifted by either optical power or base bias. Also, the nonlinear gain characteristic of the HBT makes the negative differential resistance stronger than in the simple p-i-n structure.

It is possible to conceive of two classes of applications for the integrated controller-modulator device. In one application the change in light input in the controller would alter the light passing through the modulator. The modulated light would then be an input to the next controller stage and the process could be continued. This application will require careful optical alignment of one modulator to the next stage controller and would be very useful for special optical computing architectures. Another class of application would involve an on-off optical signal to simply change the optical state of one or more modulators connected to it. The choice of the photon energy with respect to the HH exciton peak energy is usually different in the two cases. Some special functions that can be realized by the controller-modulator circuit are now briefly described.

Optoelectronic Amplification. In the use of the controller-modulator (C-M) circuit for amplification of an optical signal, a photon energy approximately 15 meV below the exciton peak at zero bias is usually chosen. The transmittance voltage curve for this choice is shown in Fig. 11.20 along

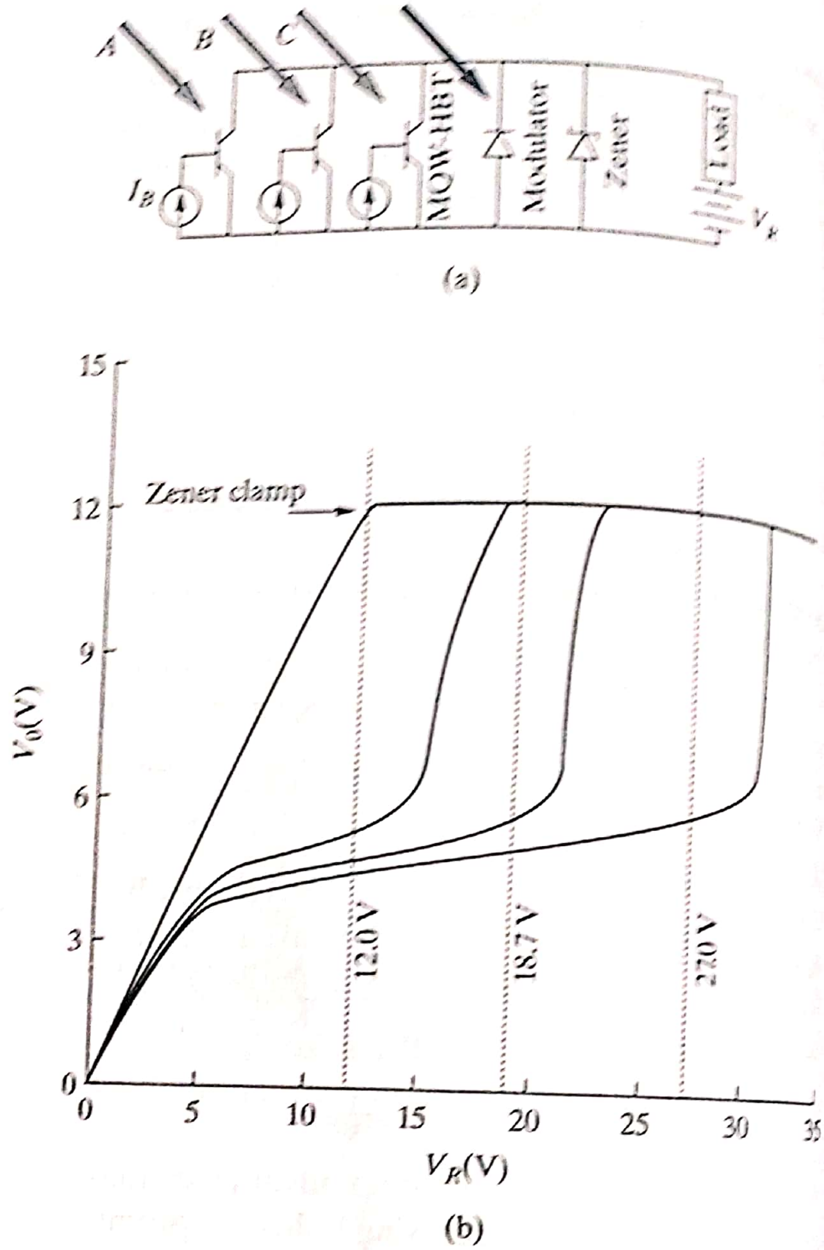

Figure 11.22
(a) Circuit diagram of a thresholding gate with three controllers and a modulator and (b) output characteristics of the gate (S. Goswami et al., *IEEE Journal of Quantum Electronics*, **28**, 1636, © 1992 IEEE).

Tunable Threshold Logic Gate. Figure 11.22(a) shows the circuit diagram of an MQW-HBT threshold gate. For operation of the gate the wavelength of the light should be above the excitonic peak, so that the complete heavy-hole response appears in the photocurrent spectrum of the MQW-HBT. The current in the load resistor is a superposition of the currents in the MQW-HBTs. The p-i(MQW)-n diodes or modulators in parallel with the MQW-HBTs are used to modulate light of the same wavelength. The photocurrent of the modulators also passes through the load, but the electronic gain of MQW-HBTs ensures that this photocurrent is much smaller than that of the MQW-HBT. Figure 11.22(b) shows the experimental output characteristics for a 3-input threshold gate. A suitable load resistance with a variable voltage supply is used. The Zener diode connected in parallel with the MQW-HBTs prevents damage from accidental high voltages. A tunable laser is used as the light source. When none of the MQW-HBTs are illuminated the output voltage increases linearly with the supply voltage, as there is no current in the circuit and hence no potential

TABLE 11.2 The Truth Table for the MQW-HBT Switching Gate at Different Voltages.

State #	Inputs			Logic Functions		
	A	B	C	NAND (V3)	ICARRY (V2)	NOR (V1)
0	0	0	0	1	1	1
1	0	0	1	1	1	0
2	0	1	0	1	1	0
3	1	0	0	1	1	0
4	0	1	1	1	0	0
5	1	0	1	1	0	0
6	1	1	0	1	0	0
7	1	1	1	0	0	0

drop across the load. From Fig. 11.22(b) it is seen that for a 12 V supply the output is 1 when none of the inputs are 1 (illuminated), but becomes 0 when any of them is 1. This is the NOR function (Table 11.2). For a supply voltage of 18.7 V, the circuit is an INVERSE CARRY gate as the output is 0 when two or more of the inputs are 1, and otherwise the output is 1. When the supply voltage is about 27 V the gate output is 0 whenever all of the inputs are 1. Hence, the gate now performs the NAND operation. Thus, the function of the gate can be altered simply by changing the supply voltage. In addition, the access to the base terminal of the MQW-HBT allows fine-tuning of the photocurrents in the MQW-HBTs so that a small optical misalignment can be compensated by electrical means.

11.6.4 Switching Speed and Energy

Optics can provide, among other advantages, massive parallelism and large connectivity. Optical processing holds the promise of reconfigurable interconnects. Optical interconnects also show a great potential for being programmable. In other words, light beams can be directed from individual sources to individual detectors on the basis of a specific command, depending on the task. This can be realized by the generalized crossbar switch shown in Fig. 11.23. In this architecture all possible inputs can be connected

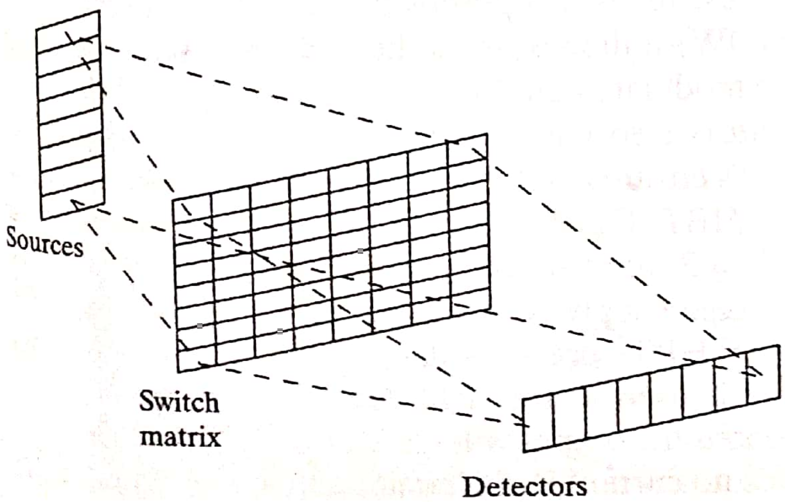

Figure 11.23 Optical crossbar switch with one-dimensional arrays of sources and detectors and a two-dimensional switch array.

to all possible outputs via the two-dimensional switch array. Each laser from the one-dimensional source array would illuminate an entire column of the two-dimensional array. Each detector from the one-dimensional detector array would receive from an entire row of the two-dimensional array. Each element of the optical- switching array could be an optical or opto-electronic switch, such as the SEED or CM device discussed in the previous section. The transmission of each individual switch could be programmed in real time, based on information coming in sequentially or in parallel. An array of SEED devices is shown in Fig. 11.24.

In a switching device the important operational parameters are switching time (or speed) and switching energy. The switching power is obtained by dividing the switching energy by switching time. The basic operating speed of a bipolar device is limited by the gain-bandwidth product. The gain required in these bipolar devices is not very large. Current gains of 10–20 are deemed sufficient. The bandwidth is then principally limited by the device capacitance, carrier transit times, and the base spreading resistance. In a simple transistor design with optimized parameters, the temporal response time, limited only by the RC time constant, is 100–500 ps, which is probably adequate for most logic applications, particularly in parallel architectures. The switching energy of the bipolar controller-modulator circuit is estimated to be 100 fJ. This optical switching energy can be reduced, at the expense of electrical energy, by increasing the base current. The switching energy can also be reduced by improved device design.

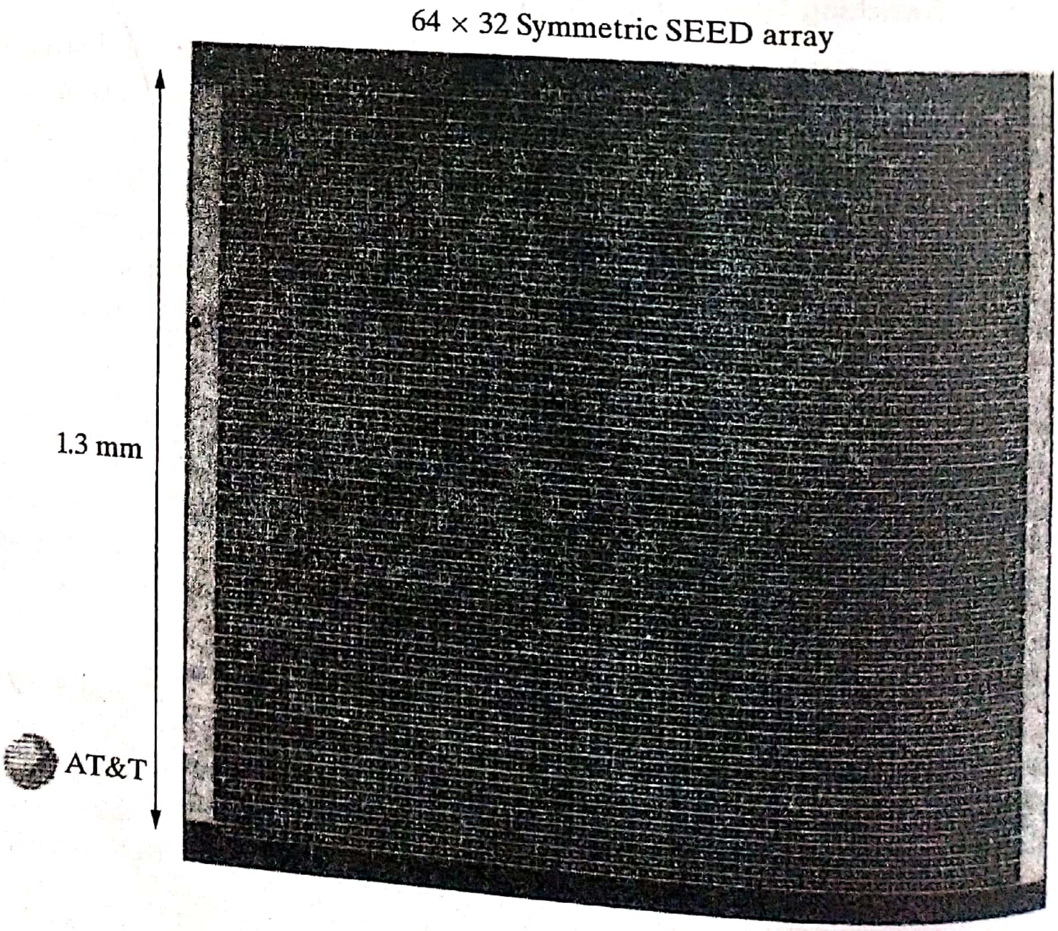

Figure 11.24
A 64 × 32 array of SEED devices (courtesy of D. A. B. Miller, AT&T Bell Laboratories. Holmdel, NJ).

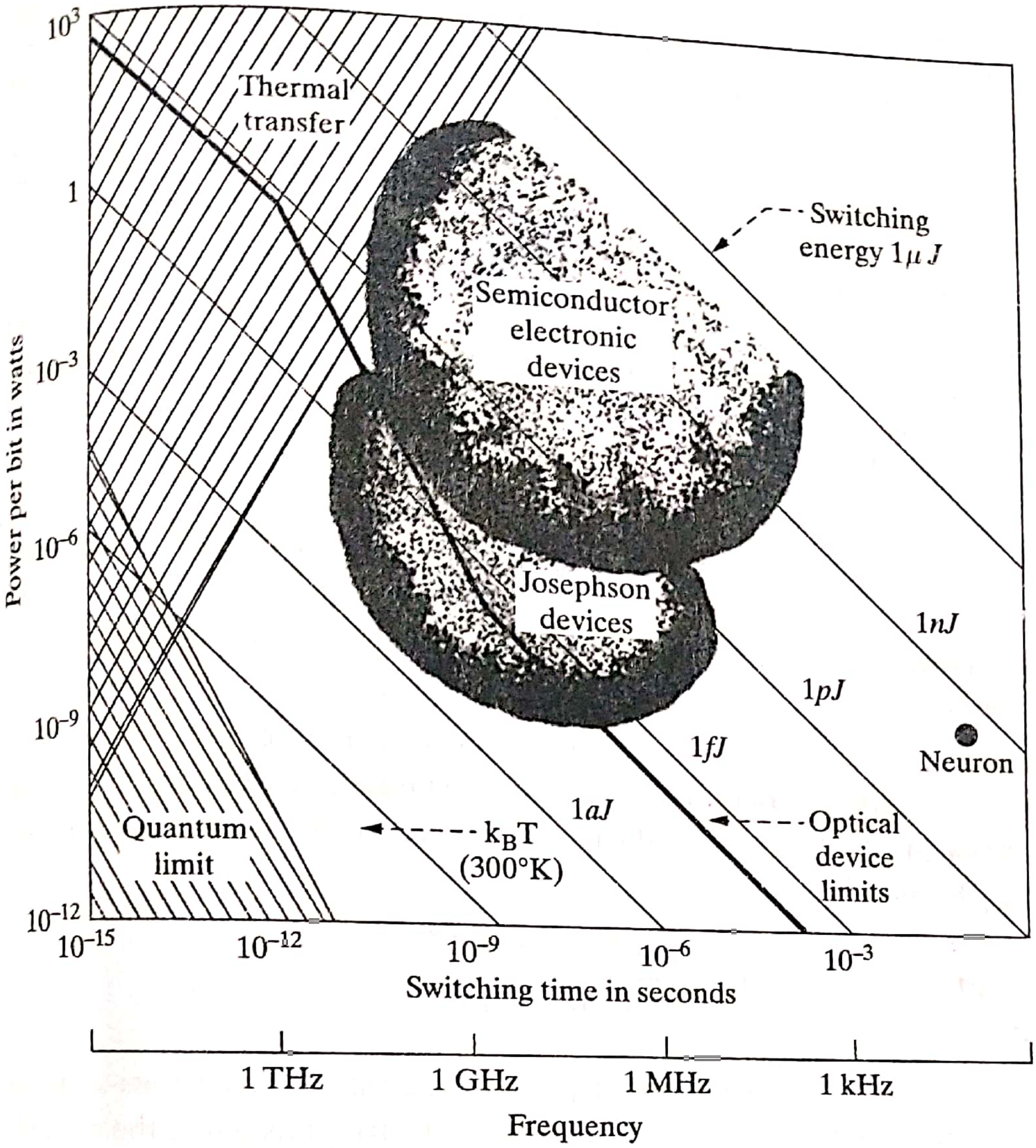

Figure 11.25 Switching powers and times for different technologies (from P. W. Smith, *Bell Syst. Tech. Journal*, **61**, 1975, 1982 Copyright © 1982 AT&T. All rights reserved. Reprinted with permission).

Only one type of modulation and switching device, based on the QCSE in quantum wells, has been described here. Many other kinds of all-optical and optoelectronic switching devices can demonstrate similar properties. Examples are bistable optical devices (BODs), also based on MQW phenomena, LEDs, junction devices, and many others. Key parameters for the success of any particular technology are switching energy and switching time. In many applications, where large arrays of such devices are required, power dissipation problems may eventually preclude a particular technology. As a concluding note, the switching powers of electronic and optical devices are shown in Fig. 11.25. It is clear that Josephson Junction devices can still outperform most technologies. It is also of interest to see how these devices compare with the *neuron*—a biological switching device.