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Quantum-well self-electro-optic effect devices

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Quantum-well self-electro-optic effect devices (SEEDs) are reviewed. The basic principles of operation in optical switching, bistability, oscillation and non-linear analogue modes are presented, and the various implementations of SEEDs are summarized. The usefulness of SEEDs in systems is also discussed, and the SEEDs are considered in the context of optical non-linearities generally.

1. Introduction

Optics has many attractive features for switching and processing applications. It is clearly very good at communicating information. It has the potential to solve many of the communications problems within processing machines as well as between them. This is true both for waveguide devices, and for the more speculative idea of 'free-space' two-dimensional arrays (for a general discussion on digital optics, see [1]). A key problem for optics lies in the shortage of suitable devices and device technologies either to perform processing functions (such as logic) or to interface with other processing devices. This is particularly severe for large digital systems. Here mechanisms and technologies are needed that allow large numbers of devices to be made and used. The physical mechanisms must therefore require low energies to avoid power source and dissipation problems. The devices must also operate in such a way that they are usable in large systems. This latter problem is one that has received less attention in optics, but as we start to move towards serious practical devices it is increasingly important. The use of large numbers of devices means, for example, that there must be no critical setting of device parameters ('critical biasing'). We cannot afford to adjust each device (for a general discussion of requirements on optical devices in digital systems, see [2]).

The quantum-well self-electro-optic effect device (SEED) concept [3–6] attempts to address both the physical and systems issues. It uses the very strong electroabsorptive effects in quantum-confined systems as a low-energy physical mechanism (for discussions of quantum-confined electroabsorption physics and applications, and non-linear optical and electro-optical effects in quantum-confined systems, see [7, 8]). It combines this with other optoelectronic and/or electronic devices to make devices that are potentially usable in systems, and which have both optical inputs and outputs. The SEEDs range from very simple devices using one quantum-well diode simultaneously as both a photodetector and

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a modulator [4] to more-complex systems that can have transistor logic incorporated with them [9]. The SEEDs discussed here can all be made using modern layered semiconductor growth techniques such as molecular beam epitaxy or metal–organic chemical vapour deposition. Such technology has reasonable prospects for manufacturing large numbers of devices. Indeed, at the time of writing, SEED arrays are now at the point of early commercial availability. Integration of other optical and electronic components and devices is promising with this technology. Such integration flexibility is also important for ultimate usefulness in systems. This paper reviews the concepts, development and status of SEEDs, and indicates possible future directions.

Section 2 briefly summarizes some of the background physics and properties of quantum wells and quantum-well modulators. SEEDs themselves are discussed in Section 3. SEEDs are discussed in the context of non-linear optics in Section 4, and Section 5 summarizes some of the features and limitations of SEEDs. Finally, conclusions are drawn in Section 6.

2. Quantum-well electroabsorption and modulators

The important physical mechanism that underlies most of the SEEDs discussed here is the quantum-confined Stark effect (QCSE) [10–12]. The QCSE gives rise to very large electroabsorption near the bandgap of quantum-well semiconductors. The basics of quantum wells and the QCSE have been extensively reviewed elsewhere [7, 8]; here only a brief summary is given.

Quantum wells usually consist of alternating thin (for example, 10 nm) layers of two semiconductors, the most investigated system being GaAs and AlGaAs. Electrons in the conduction band and holes in the valence band see minimum energy in the GaAs 'well' material, and hence see the AlGaAs layers on either side as a 'barrier'. The layers are so thin that the electrons and holes behave as 'particles in a box', just as in the elementary quantum mechanics problem. The resulting quantum confinement leads to discrete energy levels for the electron and hole, at least as far as their motion perpendicular to the layers is concerned. These levels can have energies of about 10 to 100 meV.

One result is that the optical absorption spectrum breaks up into a series of steps, with different steps associated with transitions between the different confined hole 'sub-bands' and the different confined electron sub-bands. Another consequence is that very strong absorption peaks appear at the edges of these steps, even at room temperature. These peaks are called exciton absorption peaks. When a photon is absorbed to make a valence to conduction band transition, an electron is actually created in the conduction and a positively charged hole in the valence band. The lowest-energy state of this pair is the bound hydrogen-atom-like state loosely called 'the' exciton. In bulk GaAs, such an exciton is about 30 nm in diameter. In the quantum well it is substantially smaller. It therefore has a very strong overlap of electron and hole, giving rise to strong absorption. These peaks are important for some devices.

When an electric field is applied perpendicular to the layers, the electron is pulled towards one barrier and the hole towards the other. This reduces the net energy of the electron–hole pair. As a consequence, the optical absorption associated with the creation of the pair is reduced. This means that the absorption edge 'red-shifts' with such a field. The important aspect of the quantum well is that, as this happens, the electron and hole are prevented from escaping altogether by the walls of the well. This prevents rapid 'field-ionization' of the exciton. If we try to do the same experiment in a normal semiconductor, we see predominantly a broadening of the optical absorption edge. This broadening is partly because of the lifetime broadening of the exciton peaks. By suppressing this lifetime broadening in the quantum wells, large shifts of the optical absorption edge with field can be obtained,

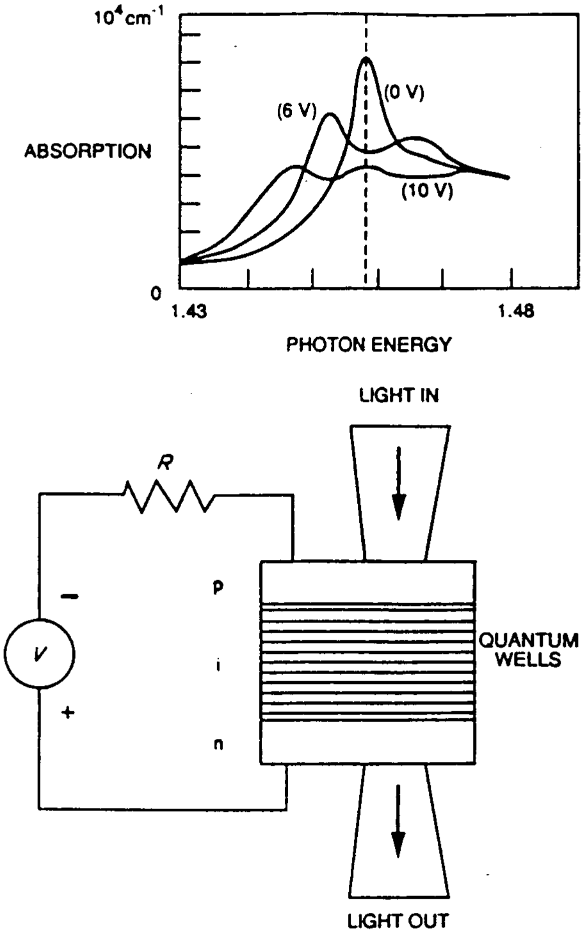

Figure 1 Quantum-confined Stark effect electroabsorption spectra at different voltages for a typical quantum well p–i–n diode [11] and circuit schematic for an R-SEED [4].

while still retaining relatively sharp and strong exciton absorption peaks. A typical set of absorption spectra with field is shown in Fig. 1 for the spectral region near the bandgap energy where most devices work. The exciton peak does become weaker as it shifts to lower photon energies. This is because the electron and hole are being pulled apart by the field, reducing their overlap somewhat. This mechanism of shifts and changes in height of the absorption features in quantum wells is the QCSE [10–12].

Because of this strong electroabsorption mechanism, quantum wells permit various new kinds of modulators to be made. This work will not be reviewed here, as it is now quite extensive (see, for example [13]). Both absorptive and refractive modulators can be made, although only the absorptive ones have so far been used in SEEDs.

The classic structure for a QCSE modulator, as used in all SEEDs so far, is a p–i–n diode as shown schematically in the circuit in Fig. 1. The intrinsic (i) region contains some quantum-well layers. As we reverse-bias this diode, we apply an electric field perpendicular to the quantum-well layers. We can make a modulator by passing a light beam either perpendicular to the layers or in the plane of the layers in a waveguide configuration. One qualitatively new aspect of such modulators is that the QCSE absorption changes are so large that useful modulation is obtained (for example, a factor of 2 or 3) even in a single pass through only 1 μm of material (corresponding to 50 or more quantum wells). Hence, two-dimensional arrays of devices can be made for arrays of light beams propagating perpendicular to the surface.

One of the major basic physical reasons for being so interested in these modulators for SEEDs and other applications is their very low operating energy. In contrast to many optical devices, the energy density required for quantum-well modulators is quite comparable with that at which electronic devices normally run. Hence, we may hope to integrate them usefully with electronics, for example.

The basic electrical energy required to change the optical properties of the quantum well is essentially the energy required to charge up the volume of the device to the operating field. This is the same as treating the device as if it were a capacitor. There is no need for the quantum-well modulators to be large if they can be integrated with the devices that drive them. For example, for perpendicular modulators or SEED arrays, 10 μm × 10 μm is quite sufficient to make a usable device. The capacitance of such a device would be about 10 fF, a capacitance comparable with that of a relatively small electronic device. The fields required to run quantum-well modulators are typically in the range 5×10^4 to $2 \times 10^5\,\mathrm{V\,cm^{-1}}$. This corresponds to voltages of the order of 5 to $20\,\mathrm{V}\,\mu\mathrm{m}^{-1}$ for devices 1 μm thick. The $5\,\mathrm{V}\,\mu\mathrm{m}^{-1}$ is somewhat higher than the best electronic devices use, so the energy density involved is somewhat larger. However, it is still respectably low, corresponding to energies of the order of $\mathrm{fJ}\,\mu\mathrm{m}^{-2}$ device area. For the case of waveguide modulators only a few quantum wells are needed in the core of the waveguide to make a usable modulator, because the modulator can be made long; for example, about 100 μm. Then the operating voltage can be lower, about 1 V, which is then compatible with most electronic devices. To date quantum-well modulators appear to offer the lowest-energy method of getting information out of an electronic system if they can be efficiently integrated with it. As is discussed below, work on SEED arrays [14–16] has shown that the operating energies of such devices do, indeed, scale down with device size, partly because these devices are fully integrated.

QCSE modulators have many other attractive features. They can be very fast, with their speed essentially limited by the time taken to apply the electric field to them. This is a usual constraint of any electrically driven device. The microscopic physics suggests that the devices could be made to work faster than 1 ps if they could be driven. Measurements on the parallel field electroabsorption have shown measurement-limited response times of 330 fs [17]. The best-demonstrated high-speed performance in a real device is currently in the range of 20 GHz [18]. They also have great potential for integration with both electronic and optical devices, such as lasers. They may be successfully integrated with multilayer dielectric stack mirrors grown in the same molecular beam epitaxy machine [19, 20]. This allows surface reflection modulators to be made. Here the light propagates through the quantum well, off the mirror and back through the quantum well again. These two passes through the quantum well improve the modulation contrast. For GaAs devices, where the substrate is opaque, removal of the substrate is also avoided. Working in reflection makes the mounting of devices easier, and this is the way in which large arrays of devices are currently being made [21, 22]. It is also possible to make interesting quantum-well modulators inside Fabry–Perot cavities formed with epitaxial mirrors both above and below the quantum wells, and this could also be applied to SEEDs [23, 24].

There are many variations on the modulator structures, on the precise physical mechanisms, and in the materials of which they can be made. Rather than reviewing these here, several of them are discussed below in the specific context of SEEDs.

3. Self-electro-optic effect devices

The modulators discussed so far are electrically controlled with optical outputs. Can devices be made that are also optically controlled? If so, we could use optics for all of the external communication of information. The idea of devices with optical inputs and outputs, such as optical logic devices, is not new. However, such devices have had many problems. They typically require too much energy, and do not have many of the requirements for devices that are usable in real digital systems [1, 2]. The SEED tries to get round these problems to give useful devices with optical inputs and outputs.

As mentioned briefly above, the basic idea of the SEED is simple. Combine quantum-well modulators with photodetectors, and possibly some other circuitry, to give devices with both optical inputs and outputs. The use of the quantum-well modulators gives optical information outputs that can use very little energy. The use of an optoelectronic system avoids many of the systems problems: some of these issues are discussed below. Incidentally, the term SEED has also subsequently been applied to other kinds of devices that utilize the concept of electrical-feedback circuits on optical elements, with the difference that the change in optical properties is from thermal effects from ohmic heating rather than the QCSE or related mechanisms [25]. Here we concentrate only on quantum-confined electroabsorptive devices.

Such an idea raises one main objection. By going to an optoelectronic system, have we not simply thrown away all of the potential advantages of optics, and acquired all of the disadvantages of electronics? It is often argued that conversion from optics to electronics and back to optics is an inefficient process. It usually is. The inefficiencies often result, however, from the fact that the system is not integrated. Hence, for example, the capacitance of wires and pads has to be charged, losing energy in the process. The lack of integration also increases cost. Systems with large numbers of devices, such as large digital systems, cannot realistically be made with non-integrated devices. It is therefore very important that such SEEDs can be integrated. It is also important that the devices can be scaled down to small sizes to make them run at low energies. Here we immediately obtain one of the advantages of quantum wells. They can be integrated, and the resultant devices can be scaled down, with proportionate improvement in performance. Hence, the communications advantages of optics can be retained in such a hybrid optoelectronic device, and they can be made in large numbers. Have we not also compromised the potential very high speed of all-optical devices by going to an optoelectronic system? Perhaps we have, but it is important to understand the role of the device switching speed in setting system performance. Large electronic systems are not usually limited in their cycle time by the intrinsic speed of electronic logic devices. Rather, it is the business of the communication of information that in various ways sets the system speed. Perhaps optics can improve the system performance without even making a faster device. Of course, we can also look in the long term for ultrafast optical logic devices, although it is difficult to envisage these in large systems in the foreseeable future because of power consumption and other issues.

We can consider the many different proposed SEEDs in two classes. The first class uses only photodiodes and passive electrical components. It is possible to make some interesting devices this way. These devices are relatively simple to make, and can be made in large numbers in arrays. When signal gain for logical fanout with such devices is needed, regenerative positive feedback can be used inside the device. This feedback can give bistability; in this case the state of the device can be changed with small power, causing large changes of output power. (The symmetrical SEED does this in a particularly interesting way because it does not require biasing the device close to threshold.) Such devices are discussed in Sections 3.1 to 3.5. Section 3.6 summarizes some of the work on the use of different quantum-well and superlattice systems to improve the operation of such SEEDs. Section 3.7 discusses the second class of SEEDs, which also incorporate transistors. In this case the transistor can also provide gain, and bistability is no longer necessary. Such devices are harder to make at present, but are promising for the future.

3.1. Resistor-biased SEED

The simplest SEED to understand is the resistor-biased SEED (R-SEED) circuit [4, 5] shown in Fig. 1. This simple circuit can show optical bistability and is a useful tutorial introduction to the first class of SEEDs. It is arguably the simplest possible way to make the QCSE into an optically controlled device with optical outputs. It does this by using the same photodiode simultaneously as the modulator and the detector.

We operate this device at the photon energy shown by the broken line in Fig. 1. In this regime, as we reduce the voltage across the diode we increase its optical absorption. Suppose that initially there is no light shining on the diode. Then all of the (reverse-bias) supply voltage will appear across the diode because there is no current flowing in the circuit. As we start to shine light, we start to get absorption. Now, as it happens, that these diodes are also very good photodiodes. For every photon that is absorbed, one electron of current is obtained. Hence, some current starts to flow in the circuit. This gives a voltage drop across the resistor, reducing the voltage across the diode. This reduction gives an increase in absorption, and hence a further increase in photocurrent. Past a certain critical 'switch-down' input power, this process can continue, leading to an ever-decreasing voltage across the diode with ever-increasing absorption. It stops when the voltage can get no smaller. This is a regenerative positive-feedback process that leads to switching into a high absorption state. Once the high absorption (low voltage) state is reached, the input power can be decreased while still retaining the high absorption, until a lower critical 'switch-up' power. At this point, the positive feedback operates in reverse, and the device switches back to a low absorption (high voltage) state. Between these two powers, the device is actually bistable; it can have either high or low transmission. This is an example of bistability from increasing absorption [26].

Another way of looking at the operation of this device is to use a simple load line analysis. This is shown graphically in Fig. 2 for the R-SEED. As with any load line analysis, two simultaneous equations are being solved. In this case, one of the equations is the photocurrent, I, generated in the quantum well diode for a given light power, P, shining on the diode. This photocurrent is shown as a function of the reverse voltage, V, across the diode as a solid line. As the diode is driven into reverse-bias, the photocurrent decreases. This is because the optical absorption decreases with increasing (reverse-bias) voltage at the wavelength at which we are working. For the simple quantum wells used here, this decrease is because the exciton absorption peak moves to lower photon energies with increasing voltage, as shown in Fig. 1. As the diode is driven into forward bias (*i.e.*, towards the far left in Fig. 2), the current decreases because of the growth of the forward current for a forward biased diode. The solid curve in Fig. 2 has been simplified for clarity but, in reality, there may be more than one 'bump' in the curve because the higher energy, light-hole exciton peak may also move down past the operating photon energy at high biases. The form of the curve is also somewhat exaggerated compared to typical devices, and the forward bias region is simplified somewhat, assuming a proportional scaling of forward

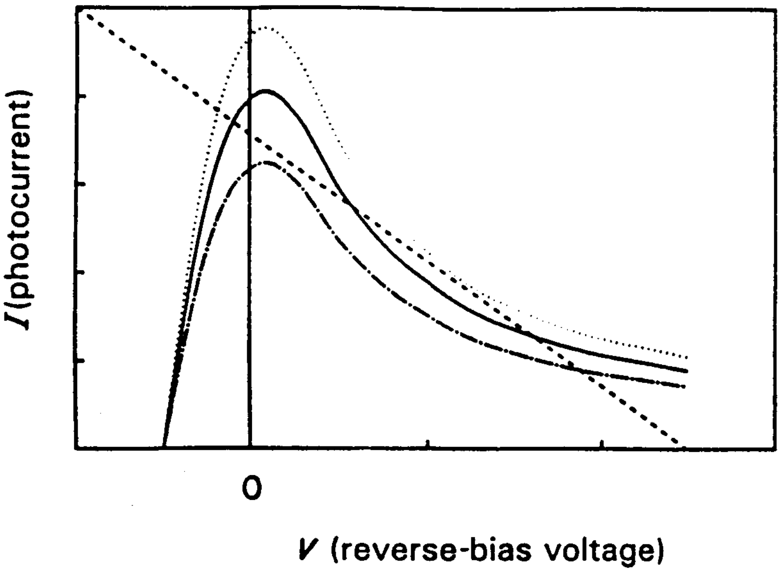

Figure 2 Simplified load-line graph for R-SEED operation. (- - -) Load-line from series resistor and power supply; (—·—) current-voltage characteristic for quantum-well diode at low incident optical power; (——) at intermediate power and (····) at high power. The intermediate-power regime is bistable, as indicated by the three intersections of line and curve.

current with light power that is not exactly justified. A good approximation is that the current at any given voltage is simply proportional to the light power, P, is reached, because the photocarrier collection efficiency is independent of power in simple photodetection. Hence, we may usefully define a responsivity $S(V) = I(V)/P$. One equation for the current in the circuit is therefore

$$I = I(V, P) = PS(V) \tag{1}$$

The other equation for this simple circuit is the relationship between the current through the resistor and the voltage V. With a supply voltage V_0 this current is simply

$$I = (V_0 - V)/R \tag{2}$$

where R is the resistance. This gives a straight broken line as shown in Fig. 2. Plotting both Equations 1 and 2 on the same curve allows us to solve for the allowed steady-state voltages of the circuit by looking at the intersections of the two lines.

In Fig. 2 the curves are plotted for three different light powers: a low power (chain-broken curve), an intermediate power (full curve) and a high power (dotted curve). At the low power it can be seen that there is only one intersection of the broken line and the chain-broken curve. This is at high voltage, and the optical absorption is relatively low. For the high-power curve there is also only one intersection, only this time it is at low voltage (actually slightly into forward bias), with a correspondingly high absorption. At powers in between, as shown by the full curve, there are actually three possible intersections. It is straightforward to show that the middle one of these intersections corresponds to an unstable point (see [5] for a further discussion). Any departure of the voltage on the diode from this point will lead to a photocurrent that charges the capacitance of the diode in such a direction as to increase further the voltage separation from this point. The opposite is true

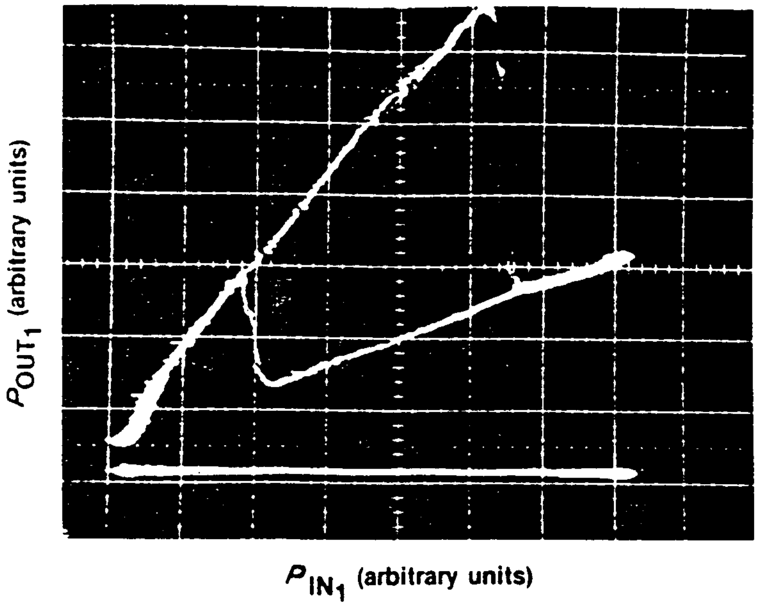

Figure 3 Optical input–output characteristic for an S-SEED, showing optical bistability [33, 34]. (This characteristic is taken with constant power shining on the second mesa of the S-SEED). Bistability characteristics are qualitatively similar for R- and D-SEEDs.

for the other two intersections. Any departures from these points result in resettling towards these points. Hence, we have bistability. One of the stable states has low absorption, and the other has high absorption. A bistable input–output characteristic for a SEED (actually a symmetric SEED discussed below) is shown in Fig. 3.

The basic dynamics of the R-SEED can be understood by viewing the diode as a capacitor. For a reverse-biased p–i–n diode this is a good approximation. The capacitance, C, of such a structure is approximately that of a plane-parallel capacitor with plates separated by the intrinsic region. The photocurrent acts to discharge the capacitance, and the resistor and power supply tend to charge it up. From this it can be deduced directly that the dominant time constant for the operation of the device is the resistor–capacitor time constant, RC.

We could switch this device from the high- into the low-voltage state by suddenly optically creating a charge $Q = CV_0$ in the diode, thereby totally discharging the diode. This requires an absorbed optical energy

$$E_s = \frac{\hbar\omega}{e} CV \qquad (3)$$

where e is the electronic charge; one electron of charge is created for each absorbed photon. In an actual device the absorbed energy will be some large fraction of the incident energy (for example, 50%), so this energy sets the overall scale of optical switching energies. In switching with slowly varying powers, the switching energy can be defined as the product of the incident power and the switching time. The resultant optical energy is still generally about E_s, although it can be several times larger depending on the precise conditions. E_s is therefore a useful characteristic optical energy for the device.

In general, E_s is comparable with or smaller than the stored electrostatic energy $\frac{1}{2}CV^2$. Interestingly, E_s really depends only on the electric field at which the device is operated, and not on how thick the quantum-well region is. This is because, in a plane-parallel capacitor, the same charge density will neutralize the field regardless of the separation of the plates. The larger the separation of the plates is, the larger the volume in which the field is reduced, and hence the more efficient the effect of the optically created charge. (We return to this point in Section 4, where SEEDs are discussed as optical non-linearities.) Formally, we can define the field $F = V/d$, and the capacitance $C = \varepsilon A/d$, where d is the plate separation in the capacitor and A is the plate area (assuming a plane-parallel capacitor). Now we can rewrite Equation 3 as

$$E_s = \varepsilon \frac{\hbar\omega}{e} AF \tag{4}$$

Note that this is independent of the separation d. This gives $E_s \approx 1.7\,\mathrm{fJ}\,\mu\mathrm{m}^{-2}$ for GaAs/AlGaAs at an operating field of $10^5\,\mathrm{V\,cm^{-1}}$. Actual demonstrated devices show measured incident optical energies for switching of about 7 to $10\,\mathrm{fJ}\,\mu\mathrm{m}^{-2}$ [16]. (In the actual device not all of the incident energy is absorbed.) This is an extremely low energy for operation of an optical non-linearity to give absorption changes of a factor of 2 or 3. Absorption saturation in semiconductors typically requires 100 to 1000 times as much energy.

An extensive discussion of switching dynamics is not given here. Much of the dynamics can be described with a simple differential equation in which the measured $S(V)$ is used [5]. However, it is instructive to look at some of the processes using the load-line analysis. Suppose we are in the high-voltage (high-transmission) state, corresponding to the right-most intersection of the full-curve and broken line in Fig. 2. As the optical input power is slowly increased, the full curve increases in size vertically. The intersection moves to the left slightly as this happens, corresponding to a slight reduction in voltage. When we get to the condition shown by the dotted curve, there is no longer any intersection at a reverse-bias voltage. The device voltage does not, of course, change instantly. As the dotted curve separates from the broken line, it can be seen that the photocurrent, as given by the dotted curve, slightly exceeds the current from the power supply through the resistor, as given by the broken line. Consequently, the voltage across the diode starts to reduce, because its capacitance is being discharged. This reduction in voltage V itself moves us leftwards in Fig. 2, thereby moving us to a point where the separation between the dotted curve and broken line is larger, further increasing the rate of discharge. This is the positive-feedback mechanism as described above. Note that there is a partial cancellation between the charging current from the resistor and the discharging current from the photocurrent. This increases the switching energy compared with the ideal minimum E_s. Note also that, in the situation shown by the broken line, although there is no longer any intersection, there is little or no current difference to drive the system towards the actual stable intersection point on the left. This is a manifestation of 'critical slowing down', an effect known well in optical bistability and phase transitions in general. Critical slowing down can substantially increase the switching times in situations where the input power is changed very slowly. It is easily eliminated, however, by overdriving the system somewhat. This can still lead to a delay in switching.

In practice, R-SEEDs usually show switching times of about RC and switching energies close to E_s. One important point is that by varying the resistor one can choose either high speed, high power operation with a low resistor value, or low speed, low power operation with a high resistor value. In this case the switching energy remains constant, independent of speed over many decades. The limit to the lowest usable power is set by the leakage current of the diode. This may be in the pA range for a very good diode, allowing operation with pW's of power. (In practice, it is difficult to make a large enough conventional resistor to exploit piocamp currents; resistances $> 1\,\mathrm{T\Omega}$ ($10^{12}\,\Omega$) would be required. This problem can be solved by using another reverse-biased photodiode as the load, as discussed below for the diode-biased SEED.) The limit to highest usable speed will probably not be set by the minimum achievable RC time, although high speeds will only be achieved in integrated devices because of stray capacitances in discrete devices. Speeds from 2 ms to 30 ns have been reported for discrete R-SEEDs [5]. The energies are essentially independent of speed over this range as expected. Other phenomena, such as the finite emission time of carriers from quantum wells and saturation of optical absorption, will probably set ultimate speed limits for SEEDs (see section 5 for further details).

It is a rather general consequence of catastrophe theory that systems bistable in the variation of one parameter are generally also bistable in the variation of others. This can be applied specifically to optical bistability [27]. This has been explicitly demonstrated for both supply voltage [5] and wavelength [28, 29] for SEEDs. Also, as mentioned earlier, the actual current/voltage characteristic is usually more complicated than the simple single-peaked curve shown in Fig. 2. When there is more than one peak in the curve, it is quite possible to get multiple bistable regions in the optical input–output curve. For the case of a simple quantum well, a second bistable loop can readily be seen resulting from the light-hole exciton peak (the weaker, higher-energy peak in Fig. 1) [5].

3.2. SEED oscillator

If we look at the curves in Fig. 2, we can see that there is a region where the (photo)current decreases as (the reverse-bias) voltage is decreased. This corresponds to negative differential conductance. (In fact, for the idealized curves in Fig. 2 this is true for the whole of the reverse-bias region.) The value of this conductance is simply the slope of the diode current–voltage curve at a given voltage and power. Increasing the optical power increases the conductance proportionately. Therefore, the quantum-well diode, with light shining on it at an appropriate wavelength, has an electrical characteristic rather like a tunnel diode. Consequently, many circuits similar to those made with tunnel diodes and other negative-resistance devices can be made. One simple circuit would be the same as in Fig. 1, and would show electrical bistability. This has been demonstrated as mentioned above [5]; ramping the power supply voltage up and down at constant optical power gives bistable switching of the voltage across the quantum-well diode. We can, if we wish, view all of the bistabilities seen with this circuit as a consequence of the negative resistance.

Another classic negative-resistance circuit is an oscillator. If we replace the resistor in Fig. 1 with an inductor, the circuit will oscillate once the magnitude of the negative differential conductance is sufficiently large to overcome the losses of the rest of the circuit, and it oscillates at the resonant frequency of the inductive–capacitive circuit. Hence, simply shining at light beam on a quantum-well diode in series with an inductor and a voltage supply can cause it to oscillate [5]. The oscillation is seen not only on the voltage across the diode, but also in the power of the transmitted light beam. This beam can be quite deeply modulated this way (for example, a factor of 2), generating an optical clock. Simple discrete bulk inductors readily give frequencies in the MHz region. This concept has not been tested in an integrated configuration, and much higher frequencies may be possible.

One extension of this concept is to make a locked oscillator that can extract the clock from a random optical bit stream [30]. If, in addition to a continuous power beam, a weak bit stream whose underlying clock frequency is close to the natural oscillation frequency of the oscillator is also injected, the frequency of the oscillator can be locked on to this clock. This is the same kind of locking that can take place with any oscillator. This has been tested experimentally with a SEED oscillator [30]. The net result is that a powerful optical clock beam is generated, locked in frequency and phase to the clock of a weak optical bit stream. This optical clock can then be used with another SEED gate to retime and amplify the signal. The whole system therefore performs all of the functions of a digital regenerator. Such a system might become of serious practical interest if it were integrated.

3.3. Diode-biased SEEDs

As a substitute for a resistor in Fig. 1, another reverse-biased photodiode could be used, giving a diode-biased SEED (D-SEED) [5] as shown in the circuit schematic in Fig. 4. As a very rough approximation, we could imagine that the photodiode behaves as a resistor whose value depends on the amount of light shining on it (this light would come from another light beam). Then it can be seen that bistability would be obtained as before. This approach has one interesting feature; the effective value of the 'resistor' is not fixed in

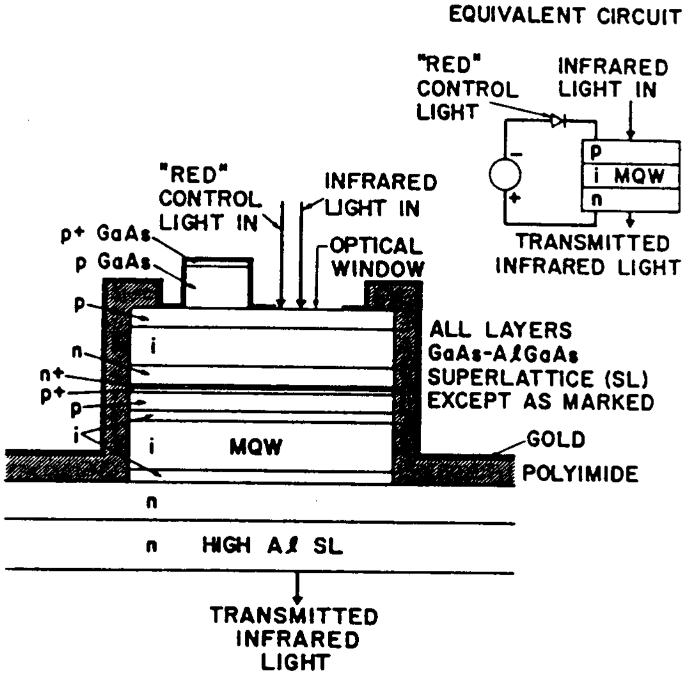

Figure 4 Layer structure and schematics for the integrated D-SEED [14]. This structure used a fine period superlattice as a substitute for AlGaAs alloy for material quality reasons. The multiple-quantum-well region contains the active quantum wells. The structure is about 6 μm thick overall.

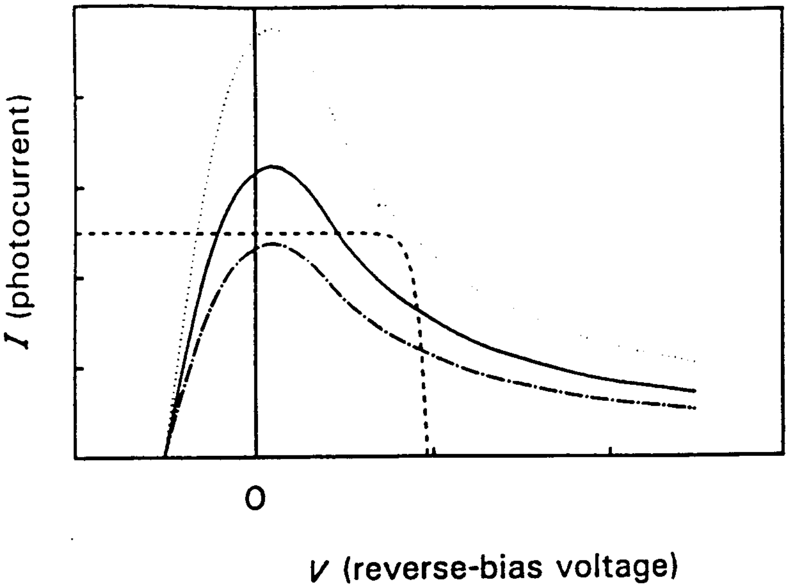

Figure 5 Simplified load-line graph for D-SEED operation. (– – –) Load-line from voltage power supply with reverse-biased conventional photodiode with constant light shining on it. Note that this behaves as a light-controlled constant-current source while the conventional photodiode is in reverse bias. (—·—) Current-voltage characteristic for quantum-well diode at low incident optical power; (——) at intermediate power and (····) at high power. The intermediate-power regime is bistable, as indicated by the three intersections of line and curve.

advance, and hence the operating power and speed of the device can be set with the amount of light on the second photodiode. More light will give faster, higher-power operation.

The use of a photodiode load also improves the performance of the device. This can be seen from a load-line analysis, as shown in Fig. 5. The load-line representing the photodiode and power supply is as shown by the broken curve. When the load photodiode is in reverse bias, the current passing through it will typically be approximately independent of the bias; in this region, therefore, the load photodiode approximates a constant-current source whose value is set by the light shining on the load diode. This is especially true if the load diode is itself a p–i–n diode. When the reverse bias on the quantum-well diode becomes comparable with or larger than the power supply voltage, the load diode starts to go into foward bias, and its (photo)current drops as shown. As can be seen, such a circuit can show bistability at lower supply voltages than required for the R-SEED. It also has a broader bistable loop than the R-SEED; the ratio of the dotted to chain-broken curves is larger in Fig. 5 than in Fig. 2, corresponding to a larger ratio of powers. Also, the separation of the (broken) load line from the (dotted) quantum-well diode characteristic is larger at most voltages than in the R-SEED case; hence, as the voltage starts to change during switching, the difference in charging and discharging currents becomes larger sooner, leading to faster switching and less critical-slowing-down. The ability to operate the D-SEED at lower supply voltages gives lower operating energy than the R-SEED. Note that in this D-SEED switching can be viewed as taking place when the photocurrent from one photodiode starts to exceed that from the other. It therefore has the unusual property that the state of the device will not change if both light beams (that is, the light beam on the quantum-well diode and the beam on the load photodiode) are changed together so that their ratio is unchanged [14]. This property is used extensively in the symmetrical SEED discussed in Section 3.4.

Another interesting SEED variation that has been demonstrated, and works well with a D-SEED, is a self-biased SEED [31]. This is a SEED without any power supply. This also works, to a lesser extent, with the R-SEED. If we take the circuit as in Fig. 1 and simply set the supply voltage to zero (that is, replace it by a short circuit), the SEED can in principle still work because of its own built-in field. In an ideal p–i–n diode the built-in field is essentially the bandgap energy divided by the thickness of the intrinsic region. This comes from the fact that the Fermi levels in the p- and n-regions must line up at zero supply voltage. The Fermi level in the n-material is essentially at the bottom of the conduction band, and that in the p-material is essentially at the top of the valence band. This self-biased SEED works best if the built-in field is large. The self-biased SEED demonstrated used a waveguide p–i–n diode with a thin intrinsic region and only two quantum wells [31]. The resultant built-in field was about $10^5\,\mathrm{V\,cm^{-1}}$. This field is sufficient to shift the exciton substantially to lower photon energies without any applied bias. As we shine light on the quantum-well diode, it starts to generate photocurrent. This drives the diode slightly to foward bias, reducing the built-in field. Consequently, the absorption increases as the exciton shifts back to higher photon energies. Hence, as before, there is a further increase in photocurrent, and so on. With sufficient light, the diode will be sufficiently into forward bias that the photocurrent collection efficiency will fall off. The current–voltage curve for such a quantum-well diode with a large built-in field will look like those in Figs 2 and 5 except that the peak of the curve will be shifted to the left into forward bias. It will therefore show bistability just as before. The practical demonstration showed bistability in a D-SEED configuration [31]. The R-SEED showed a strong kink in its optical input–output characteristic, although it was not bistable. It is easily seen from Figs 2 and 5 that the D-SEED works better than the R-SEED for low (or zero) supply voltage. The idea of a self-biased SEED, an optoelectronic device with no power supply and no external electrical connections, raises an interesting point. Is this an optoelectronic effect or an all-optical effect? We return to this point below, when discussing SEEDs as optical non-linearities in Section 4.

The D-SEED was also the first SEED to be integrated [14, 15]. The layer structure for doing this is shown in Fig. 4. Here the load photodiode is an AlGaAs p–i–n diode grown vertically on top of the quantum-well diode. In operation, a short-wavelength beam (for example, a red light beam) is shone on the top of the structure, so that it is absorbed entirely in the AlGaAs diode. This beam sets the effective 'resistance' of the load AlGaAs diode. An infrared beam, at the appropriate wavelength for the quantum-well exciton peak, is also shone on the top (or on the bottom). It passes through the AlGaAs diode without absorption. Then bistability is seen in the transmitted infrared beam as would be expected, with the switching power and speed set by the power of the red beam.

There is one subtlety in the actual layer structure used to implement this vertical integration. If two diodes are grown one on top of the other, effectively a p–n–p–n layer sequence is obtained. As a consequence, there are two possible transistors buried in the structure. Numbering the p–n–p–n layers as 1 to 4, there is a p–n–p transistor from layers 1 to 3 and an n–p–n transistor from layers 2 to 4. Since layer 1 is biased negative with respect to layer 4, layers 1, 2 and 3 are the collector, base and emitter, respectively, of the p–n–p transistor, and layers 2, 3 and 4 are the emitter, base and collector of the n–p–n transistor. In each case the quantum wells are in the base–collector depletion region (actually the intrinsic region). This means that any photocurrent generated by absorption in either quantum-well region will be amplified by the appropriate transistor gain when the base-collector junction is reverse-biased. At first sight this seems useful, since transistor gain could reduce the operating power. However, because of Miller capacitance, a phenomenon known well in transistors, it does not reduce the operating energy, and hence does not reduce the switching power for a given switching speed; we return to this in Section 3.7 when discussing integration with electronics. Since we can already run the integrated D-SEED at as low a power as we wish, there is therefore limited benefit. The transistors bring with them other problems. One problem is that transistor gain is often strongly dependent on extraneous effects such as interface states and surface recombination. This would make the device dependent on such irreproducible effects, would make it difficult to make uniform arrays of devices and would inhibit scaling to smaller dimensions; bipolar transistors are particularly sensitive to surface recombination effects as they are made smaller (the ratio of perimeter surface area to junction area increases as the device is made smaller). To avoid these problems, the structure in Fig. 5 incorporates an 'internal ohmic contact' between the two series diodes. This is actually a tunnel junction, formed by adjacent heavily doped n- and p-regions. The tunnel junction is not operating as a negative-resistance device here. Its function is as a current converter. Electrical current that flows into one side of the tunnel junction as holes flows out of the other as electrons and vice versa. (Of course, the electrons and holes themselves flow in opposite directions.) This means that there is no minority carrier injection from emitter to base in either transistor. Consequently, the transistor has no gain. (Formally, the emitter injection efficiency is zero.) The circuit behaves like two separate diodes connected by a wire. The disadvantage of using a tunnel junction is that it is difficult to make a good buried tunnel junction. The doping levels required are very high to make a diode with high current-carrying capability in the tunnelling mode. In fact, this current density limits the usable speed of this particular device in practice. Minimum switching speeds demonstrated are about 1 μs.

With this vertical structure, it is relatively straightforward in principle to make arrays of devices. These consist of mesas with insulators deposited on the sides, with a common top contact taken off the top of all of the mesas, and the bottom n-layer in the structure used as the other power supply contact. There is therefore only one pair of electrical connections for the entire array. All of the devices in the array are reverse-biased in parallel. An important point to note about this device is that the only capacitance that charges and discharges in normal device operation is the internal capacitance of the device. Although the device is internally partly electronic, there is no external electrical communication of information, and hence no lines to charge. All of the information is communicated optically. This means that we can scale the device to smaller dimensions and proportionately improve its performance.

Integrated D-SEEDs have been demonstrated in 2 × 2 arrays of 200 × 200 μm mesas [14], and in 6 × 6 arrays of smaller (60 × 60 μm) devices [15]. The devices were very uniform in their performance across the arrays. Performance also scaled well with area [15]. Operating speed could be varied from about 1 μs to 10 s with a reciprocal speed–power trade-off. For example, for the smaller devices a switching power of 180 μW was required for switching at 1 μs. Switching with as little as 40 pW was observed. The slowest switching time in the device was limited only by the leakage current in the diodes, which was of the order of pA.

As mentioned already, this device is unusual in that its bistable switching power is not set in advance, but is controlled by another (red) light beam. If we are prepared to vary both light beams, we can operate the device in ways not possible with conventional optical bistability. We can also set and reset the device by changing the red light beam, for example, without changing the infrared beam at all. Another unusual mode is to run the device as a dynamic memory [15]. As mentioned above, both beam powers may be turned down together, and the device will hold its state. Hence, memory may be held with little power, only turning up the beams when it is wanted to read out or rapidly change state, as in a dynamic memory. In fact, the beams may be turned off completely for a limited period. The device will start to change state by discharging its internal capacitance through the difference in the leakage currents in the two diodes. If we do not let this go to far, then we may turn both light beams on again and the device will latch back into its previous state. Hence, we have a dynamic memory without the sense amplifiers normally required in electronic implementations. Zero-power holding times as long as 30 s have been demonstrated [15]. The steady-state holding power for such a memory is only about 250 nW cm^{-2}.

Most of the work on SEEDs has concentrated on devices for digital applications. The devices also have analogue modes. Such modes may be useful in spatial light modulator applications or in optical neural networks. One interesting mode of the D-SEED is the self-linearized modulator or optical level shifter [5, 15, 32]. Suppose we change the operating wavelength or photon energy such that it is at lower photon energies, below the zero-field exciton peak position (that is, to the left of the broken line in Fig. 1). Then, instead of a positive feedback (giving bistability), a negative feedback is obtained. This negative feedback is particularly interesting if the quantum-well diode is driven with a current source. Suppose there is a current source attempting to pass a current I_c through the quantum-well diode. A current source is simply a circuit that passes the same current independent of the voltage. Suppose the photocurrent from the quantum-well diode, I_p, is $< I_c$. Then the quantum-well diode will charge up. For this operating wavelength, however, this increase in voltage increases the absorption and hence the photocurrent. Hence, it can be seen that I_p will attempt to increase, and will tend to settle to the value I_c. A similar settling will take place for $I_p > I_c$, in which case I_p will decrease by reducing the voltage over the quantum-well diode. Hence, there is an internal negative-feedback process that sets the photocurrent in the quantum-well diode equal to the driving current. In the particular common situation where there is one electron of current for each absorbed photon, we now have a modulator that absorbs an amount of power linearly proportional to the drive current, a self-linearized modulator. If the current is held constant and the optical input power is varied, we have a device that subtracts a constant power from the light beam on its way through, an optical 'level shifter'. In both the self-linearized modulator and the optical level shifter the output power range is, of course, limited by the minimum and maximum absorption of the diode at the operating wavelength.

One particularly easy and interesting way to make a constant current source is, of course, a reverse-biased photodiode, which is exactly the circuit of the D-SEED. This self-linearized operation has been demonstrated with both discrete [5, 28] and integrated [15] D-SEEDs. Since the current from the conventional reverse-biased photodiode can be linearly proportional to the light incident on it, a self-linearized light-by-light modulator is possible. Note that this is an inverting device, since more light on the conventional diode gives more absorption in the quantum-well diode. Since the incident light need not be coherent or narrowband, we can also have a linear (inverting) incoherent-to-coherent converter. In fact, the incident light could be a visible, incoherent image on an array of D-SEEDs, in which case it would be possible to form a linear, inverted replica of it in a coherent infrared image [15]. It is also, of course, possible to use a similar visible image on to a D-SEED array operating in the bistable mode, in which case a threshold version of the image can be formed [15]. These various modes have all been demonstrated with a 6 × 6 D-SEED array.

3.4. Symmetric SEED

The D-SEED arrays are good optically bistable devices by relative standards, both in their operating powers and speeds, and in the uniformity with which large arrays can be made. Unfortunately, they are threshold devices. To obtain the gain necessary for operation of any logic system, such devices are biased with a power supply (in this case, an optical power beam) close to their switching threshold. Then a small additional input power will trip the device over its threshold into another state. Thus, a large change in output power can be achieved with a small change in input power, giving the desired gain. There are two problems with such devices: they require very accurate setting of the bias conditions, otherwise known as 'critical biasing'; and they are sensitive to reflections of the output back into itself, which can switch the device (that is, there is poor 'input–output isolation'). In electrical terms, these are characteristics of 'two-terminal' devices (such as tunnel diodes). For these reasons 'two-terminal' devices are seldom used in large logic systems. Instead, 'three-terminal' devices like transistors are used, which are not critically biased and have good input–output isolation.

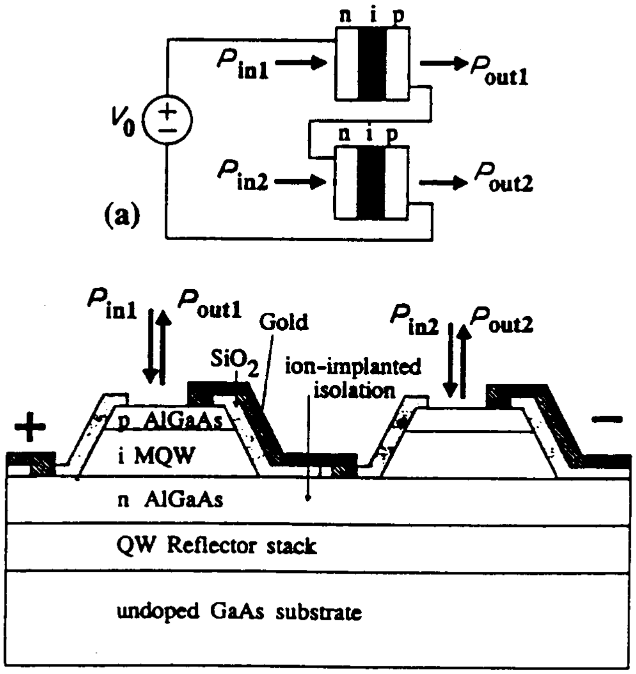

Figure 6 Schematic diagram of an S-SEED [16].

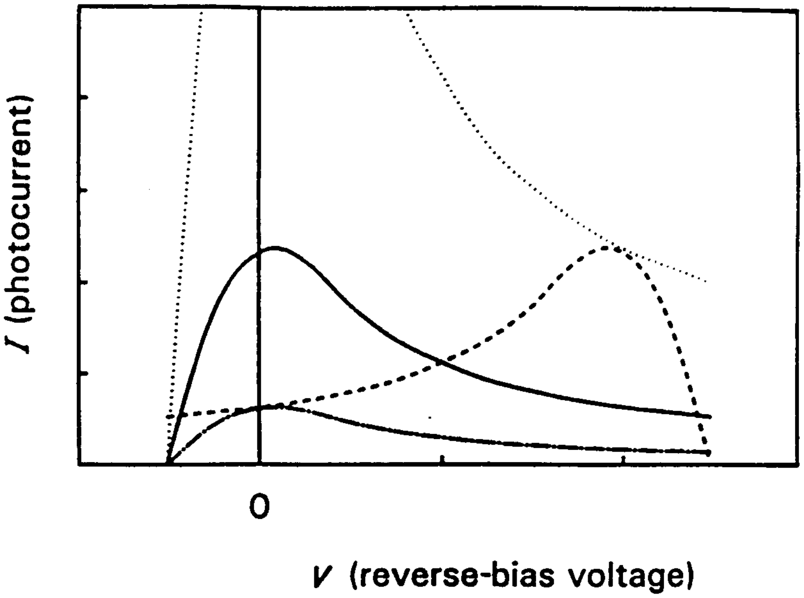

Figure 7 Simplified load-line graph for S-SEED operation. (– – –) Load-line from voltage power supply with reverse-biased quantum-well diode 1 with constant light shining on it. (—·—) Current–voltage characteristic for quantum-well diode 2 at low incident optical power; (——) at intermediate power and (· · · ·) at high power. The intermediate-power regime is bistable as indicated by the three intersections of line and curve.

The symmetric SEED (S-SEED) [33, 34] solves these problems of bistability. It is still a simple device, not requiring integration of transistors to make it work. Hence, it has already been possible to make very large functioning arrays with good performance [21, 22]. The S-SEED is also a bistable device, but it is bistable in the ratio of two light-beam powers. Instead of having a resistor or a conventional photodiode as the 'load' for the quantum-well diode, it uses another quantum-well diode, as shown in Fig. 6 [33]. Imagine for the moment that a constant power shines on one diode. Then it can be seen that bistability will be obtained in the transmission of the other beam through the other diode just as was argued for the D-SEED above. Of course, we can reverse the roles of the two diodes, and obtain bistability in the transmission of the first diode. The S-SEED retains many of the useful features of the D-SEED, such as the ability to operate as a dynamic memory.

Fig. 7 shows the idealized load line analysis for the S-SEED. We can follow exactly similar arguments as for the R-SEED and D-SEED. For the particular case of Fig. 7, a somewhat larger supply voltage has been chosen than for the D-SEED in order to exaggerate the differences. The S-SEED clearly has a very wide bistable loop (the ratio of the switching powers being given by the ratio of the dotted and chain-broken curves as before). There is even more separation of the dotted and broken curves, showing that the S-SEED should have even less problem with critical slowing down than the D-SEED. Hence, the S-SEED has quantitatively better performance features than the D-SEED. A device like an R-SEED has been demonstrated with a tunnel diode as the load instead of a resistor [35]. The inherent negative resistance of the tunnel diode has similar benefits to the quantum-well diode load of the S-SEED, although without the additional flexibility of the two-beam operation of the S-SEED.

The real difference with the S-SEED is, however, qualitative. This difference distinguishes it from all other forms of optical bistability. Suppose we shine essentially equal powers on the two diodes, perhaps derived from one laser with a beamsplitter. The device will be in one or other bistable state, with one diode transmitting and the other diode absorbing. Suppose now we turn down the power in both beams together (for example, by reducing the laser power). As we do this, we will not cause the device to change state. The device actually switches only when the photocurrent in one diode starts to exceed the photo current in the other, hence causing the voltage across the diodes to change. This is similar to the D-SEED. Provided we reduce both beams together, there will be no change in the ratio of the photocurrents. This allows us to obtain signal gain in an unusual way. We may turn down the power in both beams simultaneously, then switch the device with additional low-power input beams. Then we may turn up the power and read the device at high power. Thus, with low-power input beams we have caused a large change in output power, giving gain. This gain is unusual, as the input and output occur at different times, and hence is called 'time-sequential gain'. Importantly, we can have this gain without ever having to bias very close to a switching threshold: we have avoided critical biasing. In fact, the device is now completely insensitive to fluctuations in the power supply beams, provided they are both derived from the same laser. (The fact that the device is also tolerant to fluctuations in one beam, because it is not critically biased, means that it is not even necessary to derive both beams from the same source.) It also has some input–output isolation, because small reflections of the output back into the device will not switch it, since it is not biased near to a switching point. It is now effectively a 'three-terminal' device. The gain in the S-SEED can be essentially as large as wanted (for example, several orders of magnitude). The minimum power required to switch is limited only by the leakage current of the diodes. The gain–bandwidth product is, however, constant. If we choose to use lower power, we must wait proportionately longer for the switching to occur. Therefore, in digital applications we typically will use the device with only a small amount of gain (for example, × 5 to 10).

In principle the D-SEED could be operated in a similar way, but this would require two wavelengths and two lasers, with simultaneous clocking of the lasers. It also would not be possible to interchange the light beams in the pair, an option that allows inversion of the logical state. The use of two side-by-side diodes also means that the problems with the internal tunnel junction of the D-SEED can be avoided by making an external ohmic contact.

Another unusual aspect of the S-SEED is that it uses pairs of beams. The output of one device is a pair of beams; one with high power, the other with low power. The input of the next device is also such a pair of beams. As its input the S-SEED is actually sensitive to the ratio of these two beams. This is important, since it avoids the need for high contrast in the modulators. In electronics, logic levels do not need to have high contrast; for example, a logic '1' might be anything > 3.5 V and a logic '0' might be anything < 1.5 V. The reason why this can be done is that each logic gate actually has an internal reference voltage to which it compares. Such internal references are difficult to implement in optics. The S-SEED solves this problem because the light beams carry round there own reference: one light beam is the reference for the other. A logic '1' is one beam more powerful than the other, a logic '0' is the reverse. Incidentally, this makes the logic level essentially independent of attenuation, as long as both beams are attenuated equally.

Although it is simple device, the S-SEED is a complete logic device, with all of the basic requirements for use in a digital logic system. It can perform logic operations [30], including all of NOR, NAND, OR and AND. For example, by presetting the device in one state, it can operate as a NAND gate; only if both pairs of input beams represent a logic '1' will the device switch to the other state. Inversion occurs because the diode with larger input power becomes more absorbing after switching. Presetting can be done with a short-wavelength beam on one diode, or by using two separate infrared sources for the two mesas of the SEED; in the latter case the device can be preset by changing the power of one of the beams.

S-SEEDs have been batch-fabricated [21] in arrays. Several different mesa sizes have been used, allowing testing of the scaling of the devices with area [16]. In all of these devices, with sizes ranging from 100 μm × 100 μm to 14 μm × 13.5 μm, the minimum incident optical energy per unit device area to achieve switching was 7 to 10 fJ μm^{-2} at 15 V supply, corresponding to 3.5 pJ for the 14 μm × 13.5 μm device. Switching speeds as fast as 14 ns were measured without any increase in switching energy. Using short pulses from a laser as inputs, switching times < 1 ns have been observed with the 14 μm × 13.5 μm devices [16]. This fast switching did, however, require larger energy; 22 pJ was required at 22 V supply voltage for the sub-nanosecond switching in these devices. This higher energy was probably because of saturation. Redesign of the quantum wells is likely to eliminate this problem, and this is discussed in Section 5. The largest array of devices fabricated so far is a 64 × 32 array of devices with 10 μm × 10 μm mesas [22]. Measured switching energies on this device ranged from about 1 to about 2.5 pJ for supply voltages from 6 to 15 V with associated contrast ratios of 3 : 1 to 5 : 1. These are all reflection-mode devices. The devices in arrays are very uniform, with the input–output characteristics typically lying on top of one another when displayed on an oscilloscope. A picture of this array is shown in Fig. 8.

Because of the availability of arrays, and because the devices have the necesssary attributes for use in digital systems, it has been possible to perform some first systems experiments with S-SEEDs. Cascadability of the devices was simply demonstrated by making a ring counter circuit [34]. This optical circuit is typical of S-SEED operation. Two devices are connected optically, with the output of one going to the input of the other and vice versa. One of these interconnections is inverting (that is, the pair of output beams is crossed before being imaged on to the input of the next device). The two devices are clocked in antiphase; when the clock power is high on both mesas of one device, it is low on both mesas of the second device. Hence, the state of the second device can be changed by the outputs from the first device, because it is running at low power and is therefore sensitive to inputs. Then the clock powers are reversed, and the output of the second device then changes the state of the first, and so on. The use of antiphase clocking on successive arrays is necesssary in S-SEED circuits, since this is how we get the (time-sequential) gain. A two-bit shift register has also been demonstrated using four S-SEEDs [36]. The optics used for these kinds of systems is innovative in itself. A general module for operating S-SEEDs has been discussed [37]. More than 200 S-SEEDs on one array have been operated simultaneously [38] from one light source, demonstrating the tolerance of the devices that comes from the absence of critical biasing. These first systems experiments represent only proofs of principle. The physical performance in these experiments is not yet of practical interest. One main reason is that these experiments are done using low-power laser diodes as the power sources. The experiments have usually also been done on older generations of devices with poorer performance. That experiments can be performed under such non-optimal conditions is useful in itself. Issues such as optics and architectures can then be addressed independently of device performance or available laser power.

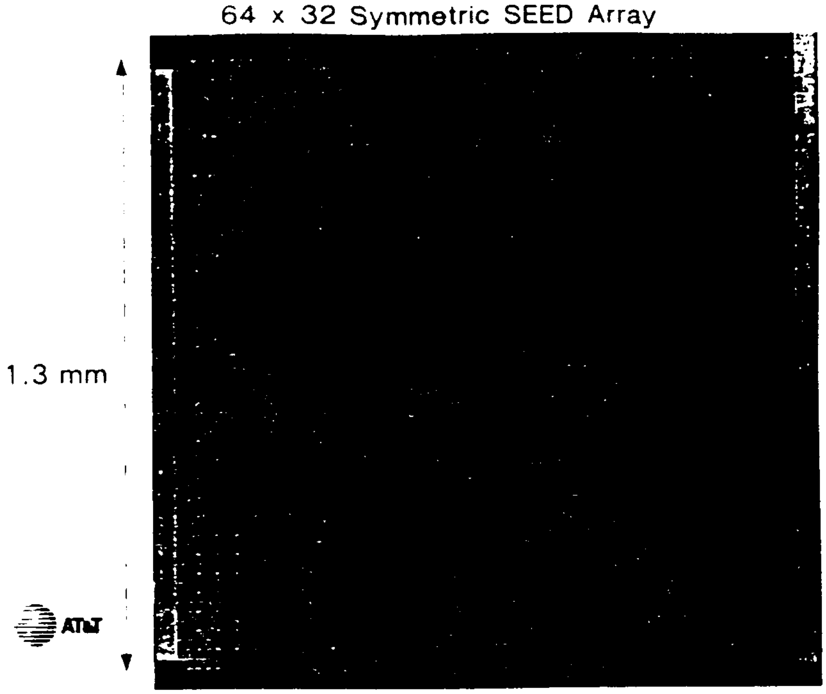

Figure 8 64 × 32 array of S-SEEDs [22]. **The individual mesas in the array are 10 μm × 10 μm.**

3.5. Extensions of symmetric SEEDs

Another way of running the S-SEED is in a 'sense amplifier' mode [39]. Here we take advantage of some degree of critical biasing to reduce the switching energy of the device. The concept is that we arrange for the device to be prepared so that it is essentially near to the central, unstable intersection of the full and broken curves in Fig. 7. Now only a small difference in input powers on the two diodes is sufficient to cause it to choose one state over the other. In this case not all of the energy for switching need come from the incoming signal beams; instead, more of it can come from the power supply beams. One way of arranging this preparation is to turn off the electrical power supply. This forces both diodes to assume equal or nearly equal voltages. If the power supply is turned back on with no light shining on the diodes, they will come up in the state with approximately equal voltages. Another way is to shine equal short-wavelength light beams on both diodes. Since in this case the absorption, and hence the photocurrent, will be approximately equal for both diodes, they will tend to settle at equal voltages. Even better would be to shine light just below the bandgap on both diodes. Then the negative feedback described above for self-linearized modulators would force both diodes to equal voltages. This concept has been demonstrated experimentally [39]. Reductions of optical switching energy of up to a factor of 10 were seen.

It is an interesting exercise to examine what happens when we extend the S-SEED concept to more than two diodes in series. This has been examined, and a method has been devised to deduce the stable states of such a system with arbitrary light inputs [40]. Two limiting cases are relatively straightforward to understand in this so-called multistate SEED (M-SEED) [40]. In both of these cases we are interested in the stable states with equal light powers on all diodes. One case is with a constant voltage supply, the other with constant current.

In the constant-voltage case the stable states correspond to one diode with all of the reverse bias voltage; that is, one diode transmitting and all others absorbing. If we had two diodes in reverse bias, one diode would be generating slightly more photocurrent than the other; this diode would discharge. Because the overall voltage is conserved, the other diode would charge up. This would continue until one diode had all of the reverse voltage. A similar process could be used to select the weakest of N beams. Suppose we turn off the voltage supply, and shine N beams on the N diodes. The one with the least power will generate the least current. As we now turn on the voltage supply, this diode will be the one that acquires all of the reverse voltage. Thus, we have a 'loser takes all' circuit; the diode with the weakest beam becomes the most transmitting. If we now illuminate with equal beams, this will be remembered. This kind of function might have some applications in artificial neural networks.

In the constant–current case each of the diodes may be either in its transmitting state or in its absorbing state. This is easy to understand if we note that the quantum-well diode current must increase at sufficiently high reverse voltage, because of avalanche breakdown. Therefore, a horizontal load-line, if sufficiently high, will make three intersections with the quantum-well diode current–voltage characteristic. As before, two of these are stable, and the middle one is not. The load-line for a constant current source with arbitrarily large output voltage is simply a horizontal line. Hence, each diode is independently bistable; the states of the other diodes are irrelevant. We could therefore make an N-bit memory with N series diodes and a constant-current load.

A concept related to the M-SEED is the 'tristate' device. The term 'tristate' refers to a concept used in electrical bus architectures. A tristate device can be 'on', 'off' or disabled. Such devices are designed to be connected in parallel. In such a bus architecture all devices will be disabled except one, which will be either on or off. The disabled devices do not 'short out' the state of the active device. By using three quantum-well diodes in series, we can achieve the same kind of operation optically [41]. With a strong light beam on one diode, the other two operate like an S-SEED with 'on' and 'off' states. With no light on the first diode, the output beams from the other two are equal (and of relatively low power), corresponding to the disabled state.

Recently the M-SEED concept has been utilized to make more complex logic circuits [42]. These circuits are analogues of n-channel metal-oxide-Si (n-MOS) and complementary metal-oxide-Si (CMOS) electronic logic circuits.

3.6. Different quantum-well systems for SEEDs

To date, most of the QCSE modulators have used simple quantum wells consisting, for example, of single GaAs layers between AlGaAs barriers. However, we can change both the materials system and the form of the quantum wells themselves.

Bistable SEEDs have been successfully demonstrated in InGaAs/InP quantum wells, operating at 1.6 μm [43]. The particular device demonstrated did have some problems with saturation at low optical powers. This prevented high-speed operation. The saturation was attributed to space-charge build-up inside the diode. In InGaAs/InP the InP layer is particularly high for the holes in the valence band. It may therefore be that photogenerated electrons escape rapidly from the wells to the positive electrode, but that the photogenerated holes are left behind in the wells. This leads to a net space-charge field that can screen the field inside the intrinsic region of the diode. This screening interferes with the normal operation of the SEED. It may be possible to solve this with improved design of the quantum wells. A SEED has also been successfully demonstrated at 971 nm in strained InGaAs/GaAs quantum wells [44].

By making a circuit like an S-SEED, but in which one quantum-well diode is a GaAs/AlGaAs diode and the other is an InGaAs/InP diode, we can make a 'wavelength converter' [43]. In such a circuit, shining a variable beam at 1.6 μm wavelength on the InGaAs/InP diode and a constant beam at 850 nm wavelength on the GaAs/AlGaAs diode allows us to transfer the modulation from the 1.6 μm beam to the 850 nm beam. We could also operate this device the other way round, using a varying 850 nm beam and a fixed 1.6 μm beam. The transfer of modulation is not linear, although this need not be a disadvantage. Using the device in a bistable mode might actually 'clean up' the modulation by forcing the beam to represent either a logic 1 or a logic 0 in a digital system.

Much more complex quantum wells can be made in which the well itself consists of various layers or is not made up of one uniform material. One example of another kind of structure that works quite well is one consisting of two thin quantum wells situated very close to one another, separated only by a very thin barrier [45]. This coupled well forms one composite well between two thicker barriers. In this case, as the field is applied the electron is essentially pulled all the way over into one well and the hole all the way over into the other. In the process we have changed the electron and hole from being 'delocalized' (that is, spread over two wells) to being 'localized' (that is, concentrated within one well). This means that there is very little overlap between electron and hole, so that the probability of finding them in the same place is very low, and hence the optical absorption is very low. In this case the modulator can be viewed as working by changing the strength of the optical absorption rather than by shifting the optical absorption edge. (The lowest transition does, of course, shift substantially.) These modulators work well, and potentially may have higher contrast than a conventional rectangular well modulator. They also show bistability in a SEED configuration [45].

An alternative view of the same absorption phenomenon in coupled wells is to say we have 'blue-shifted' the effective absorption edge. This is the terminology used in recent discussions of the same effect [46, 47]. As we localize the electron and hole, we make the lowest allowed transition weaker, as described by pulling the electron and hole into opposite wells. However, in compensation some of the higher-energy transitions become progressively stronger. In particular, the transitions between holes and electrons localized in the same well become stronger. Since these transitions are at higher energy than the original lowest electron–hole transition in the unbiased coupled system, the absorption edge can be viewed as having been 'blue-shifted' with the applied field. This is not a true blue-shift, because the lowest transition has red-shifted, although it has become very weak. We refer to this kind of effect as a pseudo-blue-shift, to distinguish it from a true blue-shift of the lowest absorption transition that can be seen in other asymmetrical structures.

The idea of using a 'blue-shifting' structure, in which the absorption edge shifts to higher photon energy with increasing field has several attractions for bistability [48, 49]. A conventional, 'red-shifting' SEED with a normal rectangular quantum well, is usually operated at a photon energy corresponding to the position of the heavy-hole exciton peak at zero field. Even at high field, however, there is significant absorption at this photon energy. We also rely strongly on the exciton peak. The shift of this peak contributes greatly to the reduction in absorption with increasing field, and is generally a larger effect than the underlying reduction in electron–hole overlap caused by pulling the electron and hole to opposite sides of the well. (The coupled well modulator described above was a (successful) attempt to make a modulator that worked more by changing the overlap than by shifting the exciton peak.) However, if we had a structure in which the absorption edge blue-shifted with increasing field, we could achieve essentially no absorption in the transmitting state. We could simply have shifted the absorption edge to higher energy than our photons. We could also be less reliant on good exciton peaks, and might obtain larger usable spectral bandwidth. These advantages have been discussed and bistable, blue-shifting SEEDs proposed using structures that are internally asymmetric [48, 49] (asymmetrical-well SEED (AW-SEED)). For example, making a skewed quantum well or an asymmetrical coupled well in principle allows the absorption edge to be blue-shifted with the field. This blue-shift can be viewed as coming from the applied field cancelling the built-in polarization of the electron and hole in such asymmetrical structures.

It is not clear whether useful bistable AW-SEEDs can be made using blue-shifts in such skewed or asymmetrical coupled wells in a material system such as GaAs/AlGaAs [49]. It is difficult to get enough asymmetry in such structures to obtain useful blue-shifts. However, true blue-shifting AW-SEED bistability has recently been demonstrated using InGaAs quantum wells grown strained on [1 1 1]-oriented GaAs substrates [50]. Such growth leads to piezoelectric fields inside the wells, as has been directly demonstrated for this particular system [51]. These fields can be about $10^5\,\mathrm{V\,cm^{-1}}$. Now as the applied external field is increased to cancel the built-in piezoelectric field, large blue-shifts can be obtained. Therefore bistability is obtained in regions where the absorption could become very low in the transmitting state. This bistability has been proved in principle [50], although it has not yet been tested in a usable device structure.

Another recent development has been Wannier–Stark localization in superlattices [52, 53]. This effect is very closely related to the electro-absorption effect just described for coupled quantum wells. In a superlattice without field the optical absorption does not have a very abrupt absorption edge because of the existence of minibands. However, as we apply an electric field we essentially destroy the minibands and recover states that are localized within individual periods of the superlattice. This allows a sharp absorption edge to be recovered again, and this effect can be used to make modulators. As in the coupled well, this gives a pseudo-blue-shift of the absorption edge, through an essentially similar localization phenomenon. Also, as in the coupled well, this pseudo-blue-shift can be used to demonstrate SEED optical bistability [54]. Potential advantages of the superlattices include the possibility of a large spectral range for usable operation.

It is important to mention that some of the ideas used in SEEDs are closely related to some interesting device ideas proposed by Ryvkin and co-workers using bulk semiconductors [55–61]. Some of this work is summarized in [60]. The first class of devices considered by Ryvkin used semiconductor diodes inside Fabry–Perot resonators. When operating below the bandgap energy, the absorption coefficient of the material increases with field because of the Franz–Keldysh effect. Operating in a circuit like that of the R-SEED, bistability is possible in this case in a manner analogous to the well-known saturable absorption resonator bistability. Increasing the incident intensity bleaches the absorption inside the cavity by reducing the field, because of the photocurrent voltage drop across the resistor. This bleaching increases the quality factor of the cavity, and hence gives yet greater intensity, and so on. Under the correct conditions this positive-feedback loop gives bistability. In optoelectronic terms, we now have a photocurrent that decreases as we increase the voltage, because more voltage gives more absorption, which decreases the quality factor, decreasing the net absorbed power overall. Hence, bistability and oscillators are possible. This group was also able to demonstrate bistable devices and optoelectronic oscillators without cavities operating in exactly the same way as the R-SEED and the optoelectronic oscillator discussed above. The difference in this latter case is that the electroabsorption mechanism is not the QCSE, but the exciton-broadening electroabsorption characteristic of pure bulk semiconductors at low to moderate fields. (This is essentially the same physics as the electroabsorption in quantum wells for fields parallel to the layers.) This mechanism also leads to a decrease in absorption for an increase in voltage. It is often loosely referred to as the Franz–Keldysh effect, although in fact the excitons dominate the actual electroabsorption (see [8] for a discussion of excitonic and Franz–Keldysh electroabsorption mechanisms). One potential problem with the exciton-broadening mechanisms is that the contrast ratio for switching may be more limited than in the QCSE or related effects.

It is not yet clear precisely what the best quantum-well or superlattice structure is for operating SEEDs. There is no simple answer to this, because different applications will have different requirements on attributes such as background loss, operating voltage, usable spectral region and contrast ratio. To some extent all of the structures proposed trade off one attribute against another. However, it is clear that we have many options for engineering such structures.

3.7. Incorporation of electronic components

The SEEDs discussed so far have only involved passive electrical components with the quantum-well diodes. This has the advantage that the devices are simple and are easy to integrate in large numbers. Incorporation of active electronic components, such as transistors, has two potential advantages. First, the use of electronic gain may enable us to reduce the input optical energy even further. Secondly, the use of significant amounts of electronics would enable devices to be made with much more-complex functionality between the optical inputs and outputs. One extreme limit is simply optically interconnected electronic integrated circuits using quantum-well modulators for the optical output. Both of these are attractive. They both depend on integration of a good transistor technology with the quantum-well modulators. This is not a trivial task. However, one important feature of the quantum-well modulators is that they are relatively easy to make. There are no critical etches involved in making the modulator work, for example. No small dimensions are required in the fabrication, other than the original layer growth. The devices scale very well to small sizes, so they can be made of size comparable with small transistors.

The first proposals for incorporation of transistors involved bipolar transistors to provide electronic gain [3, 6, 62–68] and to make devices that look more like conventional three-terminal devices from a functional point of view. In these transistor-biased SEED (T-SEED) structures a bipolar transistor is usually vertically integrated in the layer structure, as shown, for example, in Fig. 9. There are various other layer configurations possible. In operation, a weak light beam shines on the transistor part of the structure. This generates an amplified photocurrent. A more powerful beam shone through the modulator part of the structure will generate a larger photocurrent. However, it can be modulated with the weak beam because of the current gain of the phototransistor. A power gain is obtained because of the transistor current gain. Such devices can be run in either a bistable or a non-bistable mode, depending on the wavelength. In the non-bistable mode they can show amplified self-linearized modulation.

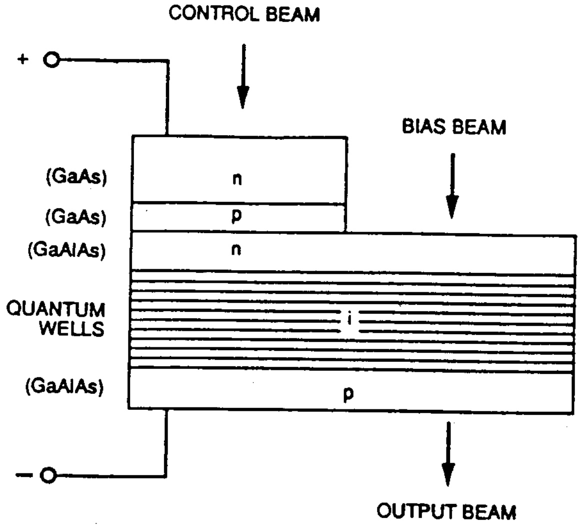

Figure 9 A T-SEED layer structure [6]. The intrinsic (i) region contains quantum wells.

It might be supposed that this T-SEED would reduce the optical switching energy requirement in proportion to the current gain. However, surprisingly, it does not. The reason for this is Miller capacitance, a phenomenon known well in vacuum-tube and transistor amplifiers. One expression of the Miller capacitance effect is to say that the base–collector (or gate–drain or grid–anode) capacitance is effectively multiplied by the voltage gain as far as the input capacitance seen at the base is concerned. This tends exactly to cancel the apparent advantage of the current gain. Miller capacitance can be understood more directly in physical terms. The basic problem is that the emitter–collector current cannot be used to charge the base–collector capacitance. If the amount of charge flowing on to the base is equal to the amount flowing off it (that is, no base current), then the net charge on the base does not change. Since the emitter–base potential is essentially fixed, the base–collector potential cannot change. In other words, the only place where we can get the necessary charge on to the base to allow charging of the base–collector capacitance is through the base contact (in a purely electrical circuit). This is true regardless of the magnitude of the emitter-collector current. Hence, the transistor current gain does not help in charging the base–collector capacitance. Thus, if there is a voltage gain, proportionately more charge must be provided in (or out) through the base to charge (or discharge) the base–collector capacitance. In the case of a floating-base phototransistor such as this, all of the base current comes from the photocurrent generated inside the base–collector depletion region. The consequence of the Miller capacitance effect in this case can be stated very simply: the base–collector capacitance is (dis)charged directly by the charge from the absorbed photons, without any benefit from the transistor gain.

The T-SEED does not, therefore, fundamentally reduce the optical switching energy compared with SEEDs without transistors. The other SEEDs have exactly the same mechanism to set the optical energy. The photogenerated charge must (dis)charge the device capacitance. Since the areas of these various devices will be essentially the same, set by optical or lithographic constraints, the energies are the same. The transistor can, however, charge any parasitic capacitance not associated with the base–collector junction, and does provide gain in a more conventional manner than the S-SEED. Offsetting this are the problems of making large numbers of transistors with the same gain, and the fact that bipolar transistors can be difficult to scale down because the gain is degraded by surface recombination. Another problem is that the transistor as shown in Fig. 9 is grown with the emitter up (that is, on the top). This is not the normal way to make a transistor, and may result in a poorer emitter–base junction and hence lower gain. By reversing the quantum-well diode, we could make a collector-up structure. The resultant n(i)pnpn unfortunately then becomes a thyristor internally, and can latch electrically, causing problems with the simple operation of this device. The solution to the Miller capacitance effect is well known; make what is effectively a two (or more)-stage amplifier in which there is little or no voltage gain in the first stage. This can be done, but not in a simple vertically integrated configuration as in Fig. 9.

Another approach is to separate the photodiode and transistor, abandoning a fully vertical integration concept. The advantage of this is that we can then use conventional planar electronic integration to make more-complex circuits. One successful approach is the field-effect transistor SEED (F-SEED) [9]. One implementation of this is shown in Fig. 10. Here we take a quantum-well diode and make field-effect transistors (FETs) directly in the top layer of the diode. From the point of view of the FETs, the processing looks exactly the same as before. A relatively standard planar FET process can be used to fabricate the transistors. With this structure, however, we find that we have a quantum-well modulator under every transistor in the circuit. In use, we would shine a beam through the structure beside the drain of the FET. As the FET switches on and off, the voltage between the drain and the bottom of the quantum-well diode changes. Hence, the voltage on the quantum-well diode changes in the region beside the drain. It can therefore be used as a direct optical output from the FET. The same diode can also be used elsewhere as a photodetector. The simple circuit shown in Fig. 10 will make an optical signal amplifier.

The FET may have an advantage over the bipolar transistor in that it is easier to make one with a low input capacitance. It is also straightforward in principle to make multistage

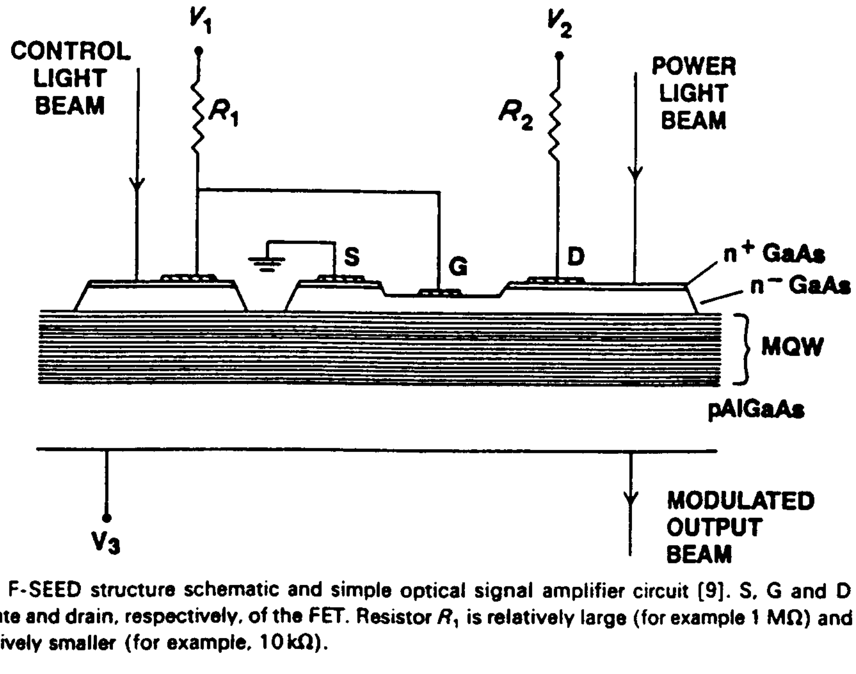

Figure 10 F-SEED structure schematic and simple optical signal amplifier circuit [9]. S, G and D are the source, gate and drain, respectively, of the FET. Resistor R_1 is relatively large (for example 1 MΩ) and resistor R_2 is relatively smaller (for example, 10 kΩ).

amplifiers to avoid Miller capacitance using the planar integration. With or without multistage amplifiers, the input optical energy can be reduced by using the voltage gain of the circuit. Less voltage swing is required on the input photodiode (*e.g.*, only ~0.5 V compared to ~5 V on a good conventional SEED). Hence proportionately less optical energy is required provided the FET input capacitance effects do not dominate.

Perhaps the most important aspect of combining the quantum well diodes with an integrated electronics technology is that it allows greater flexibility of functionality. If one integrates with a real electronic logic technology, arbitrary electronics can be interposed between optical inputs and outputs. Rather than being restricted to simple gates, more complex functional blocks or 'smart pixels' could be made. Whether it is better with more complex circuits depends on the system being made. As electronics are added, less efficient optical use of the area is made; optical inputs and outputs become more spaced out, and hence the space-bandwidth product of the lens is used less efficiently. The devices may also become harder to make. The use of more electrical interconnection is also begun. However, there are some rather fundamental arguments [69] that say it is efficient to use electrical interconnections over short distances (*e.g.*, up to 100 μm–1 mm), so the concept of optically interconnected electronic blocks is a sensible one. It is also fundamentally true, that, provided we can intimately integrate efficient optical devices such as quantum wells with electronics, we can significantly reduce the energy required for logical interconnection. The most favourable comparison for optics is not to compare the logic energies or the size of the smallest logic device, but rather to compare the communication energies and the size of the 'output pads'. Energies and sizes of good optical devices of devices such as SEEDs are certainly not better than the best electronic logic devices, although they are comparable with good electronic devices; the energies are, however, much better than electrical communication energies, especially for off-chip communications, and the sizes are much smaller than electrical bonding pads. The optical 'pads' need be no larger than 10 μm × 10 μm. The logic energy of optical devices is the same as their communication energy; no additional line-drivers are required. The reason for this is that optical devices are quantum devices, and perform an effective 'quantum impedance conversion' that matches to the low impedance of free space [69].

Another approach to the integration of quantum wells with electronics is GaAs/AlGaAs modulators on silicon substrates. This has been successfully achieved [70, 71], with performance comparable with similar modulators on GaAs substrates [70]. Initial tests also show good lifetime for these devices, with > 1000 h lifetime demonstrated without apparent degradation. This is very promising for integration of optical inputs and outputs with silicon integrated circuits. By contrast, devices such as lasers and light-emitting diodes have yet to show usable lifetimes on silicon substrates. Several technology issues remain to be resolved to integrate quantum-well devices with actual silicon integrated circuits, but these initial results are very promising.

4. SEEDs as optical non-linearities

We are historically used to thinking of non-linear optics in terms of power-series expansions of the polarization in terms of the optical electric field. This gives us coefficients such as $\chi^{(2)}$ and $\chi^{(3)}$. It is also assumed for simplicity with such non-linearities that the polarization is dependent only on the local electric field. Neither of these approaches is valid for SEEDs, nor really for any other non-linearity involving macroscopic transport of charge. Many of these remarks apply to the other non-linearities discussed elsewhere in this issue of *Optical and Quantum Electronics*.

The invalidity of the electric-field power-series approach is simply demonstrated [2, 26]. Consider a simple bistable device such as the R-SEED. The amount of power absorbed, a quantity that can be expressed in terms of the polarization of the quantum wells, is not a single-valued function of the optical electric field inside the material. Power series are always single-valued. Hence, the polarization cannot be expressed as a power series in the optical electric field. It might be argued that the polarization of the quantum wells is a single-valued function of the total field inside the material, when the d.c. field is included. This is correct. If, however, we consider for example a self-biased SEED, and try to analyse it as an optical non-linearity, it is still the case that its response is not single-valued in the externally applied optical field inside the material, and it cannot be expressed as a power series in this field. Therefore, there is a qualitative difference compared with the usual power-series non-linearities. These properties have been discussed in connection with bistability from increasing absorption [26] and other related effects [2].

The devices are also clearly non-local. For example, switching a R-SEED by shining light on one part of the quantum-well diode will change the transmission of a light beam through another part of the same diode. The device also conveniently 'forgets' the phase of the original light beam, so coherent interference effects are avoided between the beams. It also 'forgets' which part of the diode the switching beam illuminated; this means that different parts of the device can be used for independent but exactly equivalent inputs. Both of these losses of memory are because of essentially thermodynamic equilibration processes within the material.

Is it valid to view SEEDs in terms of optical non-linearities? It might be argued that they are not 'all-optical' because they involve electronic transport. This is a question of semantics; power-series non-linearities also involve electronic transport, albeit coherent electrical transport over very small distances (the electron clouds oscillate in response to the applied field). As far as the external operation of the system is concerned, however, SEEDs are clearly optically non-linear devices. Consider for example the self-biased SEED discussed above [31]. It is necessary only to put optical beams into it to get it to operate, and the interaction of those beams in the device is clearly non-linear, with one beam capable of switching the other. It is obvious, in fact, that any SEED could be run as an all-optical system by merely arranging for sufficient photodiodes to operate as a power supply for the operation of the device. (It is not, however, quite correct to say this is the function of the load photodiode in a self-biased D-SEED, since this diode also ends up in reverse bias in one of the stable states. In reverse bias, the photodiode is clearly not a power supply, since it then dissipates power.)

SEEDs are examples of a much more general class of optical non-linearity. Such an extended class includes non-local, incoherent and irreversible phenomena. Using this extended class is very important for devices. It enables many problems with the usual reversible power-series non-linearities to be avoided. The non-locality allows beams to be incident on different places, hence interference can be avoided entirely. Also, the input and output do not necessarily need to be at the same point in space, hence improving the possibilities for good input–output isolation. It is also possible to have thermodynamic irreversibility in the devices. Time-reversing the optical beams in the systems does not result in time-reversed operation of the device (for example, inputs and outputs changing roles) because it is internally irreversible through the dissipative processes inside the device (although simple bistable devices like the R-SEED can still have poor input–output isolation). This is useful for input–output isolation. Coherent light or even mutual coherence between beams is also not required. Devices can be designed that are functionally much more complex than those that can be made using conventional power-series non-linearities. Even the simple D-SEED and S-SEED can perform functions that would be very difficult to implement with power-series effects, such as bistability in the ratio of two beam powers. The additional functional complexity of, for example, the S-SEED, compared with simple bistability, is what allows them to be used successfully in digital-systems experiments. These various features are very useful in designing devices capable of being used in digital systems.

We could try to characterize some of the simpler SEEDs in terms of an effective $\chi^{(3)}$. SEEDs can operate with very low powers; for example, the integrated D-SEED can run with $< 1\ \mu\mathrm{W\,cm^{-2}}$ [14], with full switching. To achieve this with a conventional $\chi^{(3)}$ non-linearity without use of a cavity would require a $\chi^{(3)}$ of about 10^{+7}esu! This is not, however, the most meaningful number to characterize the non-linearity. Operating energy per unit area is a more useful measure of the strength of the microscopic effect. This energy is essentially independent of speed over many orders of magnitude. This is also a good number for predicting the usability of devices in large systems, which are often dominated by power source and dissipation problems. The lower the energy density is, the faster devices can be run without overheating, and the more of them can be run with a given optical power source.

We have already discussed the energy density requirements for simple SEEDs. Both optical and electrical energies are typically within the range about 1 to $30\ \mathrm{fJ\,\mu m^{-2}}$. One of the pieces of physics that makes the optical energy of SEEDs so low is the transport of photogenerated charge over substantial distances. It has this in common with other charge-transport non-linearities discussed elsewhere in this issue. One important general feature of all of these non-linearities is that the optical operating energy is inversely proportional to the distance travelled by the photogenerated charge within the structure. This is simple to understand. The change in optical properties in the material is caused by the change of electric field in all of these electroabsorptive and electrorefractive non-linearities. The change in field is caused by the transport of photogenerated charge. This movement in charge changes the field within the material. A useful model for many of these effects is to consider the charge in terms of a plane-parallel capacitor, or equivalently in terms of movement of sheets of charge; this was specifically discussed in Section 3.1 for SEEDs. In separating two sheets of opposite charge, the electric field in the volume between the sheets is independent of the separation of the sheets. We can imagine, for example, that we create sheets of electrons and holes in one quantum well within a stack of quantum wells, biased with a field perpendicular to the layers. These electrons and holes will reduce the field within that quantum well, giving some non-linear optical effect. (In fact, this effect is broadly comparable in magnitude to the size of the optical saturation effects resulting from that density.) However, as these electrons and holes are allowed to transport out of the wells in opposite directions, they will change the field in progressively more quantum wells. The larger the distance that they travel is, the larger the volume in which they change the field, and hence the more efficient the optical effect becomes. In a typical SEED the charge is allowed to travel about $1\ \mu\mathrm{m}$, making the SEED very energy-efficient. As mentioned above, it is really this effect that makes the SEED require much less optical energy than typical saturation non-linearities. The photocarriers generated in one well are used to screen the electric field in all 50 or so wells in the 1 μm thickness, giving a factor of 50 improvement in efficiency of use of optical energy; in one sense the same carriers are used 50 times. Devices or non-linearities that only screen the field within one well are not particularly efficient by comparison [72–75], whether they work by real [72] or virtual [73–75] excitation. Incidentally, the work to move the charge within the device is done by the electrical power supply. In the particular case of self-biased devices, the energy for the electrical power supply also comes from the photons, of course.

A number of authors have proposed schemes that could be categorized as 'internal' SEEDs [76–80]. In such devices there is little or no external circuity, but the basic principle is still that carriers generated by optical absorption in the quantum wells move so as to screen the field, hence changing the optical absorption in the quantum wells. An advantage of some such devices is that the lithographic fabrication is often simplified, perhaps requiring no 'pixellation' into individual mesas at all. Hence, it may be possible to use such schemes as substitutes for other optical non-linearities. It is common to look at such structures as being optically non-linear. The discussion of the energies of operation of such devices is exactly the same as for the SEEDs above, because the basic physics is identical, and hence these non-linearities are large. The same arguments also apply to the discussion of whether such structures are optically non-linear in the conventional sense. There are two disadvantages of such schemes. First, the non-linearity is usually fixed at fabrication; the operating power or speed cannot be subsequently changed. Secondly, the structures are usually capable of only simple functionality; it is more difficult to extend the functionality as in devices such as the S-SEED or the F-SEED. Higher functionality requires more fabrication complexity, but does offer real benefits to the processing system as a whole.

Most SEEDs demonstrated have not attempted to use optical cavities to improve switching. Use of cavities could obviously help in reducing some energy requirements (as well as allowing other modes of device operation [60, 81]). We could use less thickness of material by surrounding it with a resonant cavity. Note, however, that if the material is operated at the same electric field there is no saving in absorbed optical energy by use of a cavity. To screen the field with the photogenerated charge still requires the same charge per unit area, and hence the same absorbed optical energy density per unit area. However, we could probably reduce the power supply voltage, reducing the electrical energy.

Clearly, if electronic gain is incorporated, as in the F-SEED for example, the optical input energy requirement can be further reduced. The reduction will be proportional to the voltage gain of the system (provided there are no parasitic capacitances). If less optically induced voltage swing across the input photodiode is required, then proportionately less photogenerated charge on the diode is needed, and hence proportionately less optical input energy.

As we change to devices with more functionality, such as the D-SEED, the S-SEED and devices incorporating active electronic components, the concepts of non-linear optics become of less use. The resultant non-linear systems become very complex, and are better described in digital terms rather than in terms of physical power series. It appears that applications will drive us towards greater functionality in the devices, and hence away from a simple non-linear optical description.

5. Features and issues

As mentioned above, SEEDs have been used in some simple systems experiments and demonstrations. This practical experience helps to identify both problematic issues and useful practical features of the devices. Here we raise some of these points, both for and against SEEDs.

5.1. Optical power sources

One clear issue is that the devices have no internal light source. They are not primary sources of optical power. They achieve their optical power gain only by modulating some external optical power source, in a manner similar to a transistor's electrical power gain. In two-dimensional array applications they might typically use one high-power source per array. In such applications there must also be optics to generate the necessary array of beams. The optics to achieve this is novel and challenging in itself; however, systems have been demonstrated that allow both generation of uniform two-dimensional beam arrays from a single laser-diode light source and lossless combination of the input power array, the output beam array and two input arrays on to the device array [1, 36–39]. The absence of an internal light source can also be an advantage to some extent, because it means that the power loss associated with the finite efficiency of the light source is not dissipated on the chip. Another important systems advantage of a single light source in digital applications is that it is very simple to clock all of the devices together by pulsing the laser. Synchronous clocking of all of the devices in a system is otherwise difficult. In fact, distribution of a synchronous clock, which is a significant problem in electronic systems, can be solved in this way. This kind of synchronicity helps to exploit the inherent absence of clock-skew in imaging optical interconnects. (By Fermat's principle, all of the path lengths in an imaging system are essentially equal.) In analogue systems, such as those using spatial light modulators, the use of a single light source is also useful because it gives mutual coherence to all of the light beams, hence allowing the various optical filtering and correlation schemes. It is currently true, however, that if we wish to run large arrays of devices simultaneously at high rates, state-of-the-art high-power diode lasers will be needed to achieve this.

5.2. Contrast ratio

The SEEDs demonstrated so far for light propagating perpendicular to the layers do not have very large contrast ratios. Typical values in actual devices range from 2 : 1 to 8 : 1 in simple transmission or reflection modulators. The contrast ratio can be increased by use of Fabry–Perot resonators, although this requires careful tuning of the resonator during fabrication. It also may require careful choice of operating voltage to obtain the best contrast. To some extent the use of resonators therefore introduces some 'critical biasing' constraints. Under such optimum conditions, very large contrast can be achieved (for example, > 100 : 1 [23]). In digital devices high contrast is not important in itself, provided that the digital logic levels can be clearly distinguished. By using devices in a differential mode, low contrast ratio is not then a fundamental problem. This is the way in which the S-SEED is operated, and the simple principle can be applied to other systems as well if desired. As discussed above, this two-beam operation also has other advantages, including a logic level that is independent of the absolute power. The absolute change in reflectivity is, however, still important, since this sets the power difference (and hence photocurrent difference) for switching the next device. It is not clear how large the contrast ratio could be made (without resonators) if the operating voltage, capacitance and insertion loss were not crucial. A contrast of 26 : 1 has been demonstrated in a reflection modulator with 122 8 nm wells and 24 V drive [82]. In a single diode there is a limit to the amount of quantum-well thickness that can be depleted, with a consequent limit on the amount of absorption contrast. The limit is set by background impurity concentration and avalanche breakdown. Most devices are not yet working near this limit, and larger contrasts may be possible. Certainly structures with multiple diodes could be made with high contrast. Incidentally, the use of differential pairs of beams in one sense gives devices infinite contrast in an analogue application, since the difference between the two beam powers can go from positive to negative, passing through zero. The use of two beams also enables a bipolar variable to be represented (one that can be either positive or negative). Arbitrary contrast ratios can, of course, be achieved in waveguide devices by making them arbitrarily long, although insertion loss would be an issue.

5.3. Device size

The criticism is sometimes made that optical devices are limited in size by the wavelength of light. This is correct, although with current technology the real limitation in SEEDs is the lithographic fabrication technology, which is common to electronic devices as well. Such lithography results in excess stray capacitance because the electrical contacts and connections cannot be made arbitrarily small in both SEEDs and conventional electronic devices. Even so, as discussed above, the more favourable comparison for optics is to compare the optical device with the size of an electronic output pad. Optical devices need no output pads other than the device itself; the logic devices can be directly connected to devices even on another chip without any line drivers or large pads. The information flow in such devices is entirely optical, except over small distances within the devices; hence, they can exploit the communications energy advantage of optical quantum devices [69]. Current SEEDs are already operating with sizes well below those of bonding pads on integrated circuits, and already have numbers of logical input–output connections exceeding those of the largest electronic chips demonstrated. It is also fair to add that in practice with SEED arrays we are somewhat limited by the size of optical spot that can be made. Note also that in arrays it is necessary to make not just one but a large number of spots in an array; this is more demanding on the lenses and the optical system. As a guide, however, anything that can be seen with an microscope objective can probably be optically interconnected. The final lenses in such an optical system would probably have about the same optical complexity as a moderately good microscope objective, with the additional freedom that they would not need to be achromatic because the wavelength in the system would be essentially fixed.

Another important point about SEEDs is that they scale well as they are made smaller or the operating power levels are changed. Unlike laser diodes, for example, they are not threshold devices, and can be essentially equally efficient at any power and size. Conventional laser diodes are not efficient at low total powers, although they are arguably the most efficient light sources available when run under the best conditions. They cannot simply be scaled down in size; shorter lengths require proportionately higher cavity reflectivities. (An important development here is recent advances in microcavity lasers, which may help to remove this problem, although much work remains to be done there [83].) With the SEEDs there is still significant room for further scaling beyond the devices demonstrated to date. Improved processing should allow still smaller devices with less stray capacitance. Engineering of the quantum wells may also allow lower-field operation, with a proportionate improvement in operating energy.

5.4. Wavelength and temperature sensitivity

SEEDs do have a relatively narrow wavelength range for best operation. In conventional bistable SEEDs, the optimum operation with best switching contrast in high-performance devices is obtained over a range of a few nm of wavelength, although the devices are typically bistable over tens of nm. This means that the laser source must be chosen carefully. Devices could be designed with larger wavelength range at the expense of performance (for example, by using narrow quantum wells with less-distinct exciton peaks). Other well designs, such as blue-shifting structures or superlattices, can increase the useful operating wavelength range. A narrow wavelength range does introduce some sensitivity to temperature. The temperature sensitivity comes from the temperature dependence of the bandgap energy (about 0.4 meV K^{-1} or about 4 K nm^{-1} at 850 nm), a phenomenon that also affects all semiconductor laser diodes. It is not too drastic, and is seldom even noticed in laboratory demonstrations of devices. At worst, stabilization within a few degrees might be required in the devices with the narrowest operating wavelength range, and devices with tolerances of tens of degrees are likely, with some tradeoff in performance.

5.5. Saturation

An important issue with operating SEEDs at high speed is saturation [16]. If the devices are operated at high optical intensities, significant carrier densities can build up in the quantum wells. This density obviously depends on how long it takes carriers to get out of the quantum wells. There are at least two mechanisms by which the carrier density impairs device performance. One, already mentioned above [43] for the case of InGaAs/InP wells, is that one carrier type (for example, electrons) is rapidly swept out of the wells, whereas the other is not. This leads to a space-charge field that screens the field within the diode. Of course, such effects are really also SEEDs, but they cannot now be controlled by external circuit parameters, and are undesired here. This effect can probably be significantly reduced by redesign of the quantum wells for faster carrier emission, although this remains to be demonstrated. A second mechanism, which is probably the dominant one in GaAs/AlGaAs quantum wells, is direct absorption saturation of the exciton peaks. Such an effect becomes significant at densities of about 10^{17} cm^{-3} [8].

The saturation actually significantly limits the speed of devices in systems. There are two reasons for this. First, a clock energy must be put into the device that is significantly greater than the minimum switching energy, because the clock must make up for the fanout and all of the losses in the device itself and the optics, so that there is sufficient energy to switch the next device. Hence, this larger clock power must not saturate the device. The second reason is that the actual optical area illuminated by the beam is often significantly smaller than the total area of the mesa. Hence, the carrier density generated can be much higher locally than the average over the whole mesa area. Of course, such undesirable effects can be minimized by reducing the loss in the system and reducing unilluminated areas on the device by improved fabrication. However, we can also address these issues by changing the quantum-well design.

Saturation intensities in GaAs/AlGaAs quantum-well modulators have been investigated [84]. By reducing the barrier aluminium concentration (for example, to 20%) and/or reducing the barrier thickness (for example, to 3.5 nm) the saturation intensity can be increased from a few kW cm^{-2} to hundreds of kW cm^{-2}. This is probably simply a result of reducing the time taken for carriers to be emitted from the quantum wells so that they can be swept to the electrodes by the field. The emission can take place either thermoionically or by tunnelling, or probably by a combination of the two. The saturation intensities also depend on the voltage. Related measurements of the emission times show both thermionic [85, 86] and tunnelling [84, 87] emission, including resonant tunnelling contributions [87]. Reducing the carrier emission time also improves the switching speed of the devices. Using an improved design S-SEED switching in 33 ps has recently been demonstrated [88].

5.6. Other features and issues

The SEEDs discussed here all absorb power. This is true also in their nominally transmitting states; that is, there is an insertion loss. Typical bistable devices may have a maximum transmission (or reflection) of 50%. This loss does mean that we must use twice as much power in our system for the same performance. In digital applications it is not otherwise very important. Usually a fresh power supply is needed at each stage of devices, anyway. However, it is true that it would not be possible to go for many stages in a system without such supplies. On the other hand, the SEEDs do allow two-dimensional arrays of devices to be made, because the absorption effects are sufficiently strong to allow devices only micrometres thick, and some background loss may be a small price to pay for this qualitative advantage.

Most SEEDs have been made for array applications. Waveguide devices are also possible, and have been demonstrated [12, 30, 31, 45, 89]. In integrated systems such devices may yet prove useful. Certainly, very low-voltage operation is possible. Waveguide devices do show different absorption spectra in the two different possible polarizations in the waveguide. This is a rather fundamental property of the quantum wells, and stems from the loss of symmetry inherent in making a layered structure. This can be viewed as either a problem or a benefit, depending on the application. The modulation mechanism works equally well in either case, although the optimum wavelength for operation changes somewhat. One interesting possibility for waveguide systems is partial intermixing of quantum wells to shift the bandgap energy [90]. This allows different regions of the waveguide to have different bandgaps, so they may be modulators or transparent guides. The electroabsorption still works in such structures [91].

On practically useful feature of SEEDs for systems experiments is that the devices can be run very slowly at very low power. This is limited only by the leakage current of the devices, and has been demonstrated to intensities of $< 1\ \mu\mathrm{W\,cm^{-2}}$ with switching speeds of about 10 s. This flexibility permits systems experiments without the necessity of expensive high-power sources, with the reasonable prospect that the performance can be proportionately improved with higher-power sources. The slow operation is also an advantage in debugging the system, as the complete switching sequence of the systems can be followed in real time.

6. Conclusions

At the time of writing, many different SEEDs have been demonstrated with various possible functions in analogue and digital applications. The concept has proved to be flexible, and many other configurations are doubtless possible. The existing digital devices have all of the features actually required for digital logic: complete Boolean logic functionality, gain (or fanout), logic-level restoration, absence of critical biasing, and input–output isolation. They can be made in relatively large numbers with good uniformity. The devices are comparatively straightforward to make, and are apparently reliable. They have low operating energies.

comparable with those of electronics, and have the potential to tap the energy and other advantages of optical communications in digital systems. They are compatible with laser-diode light sources, and with electronic devices. Large SEED arrays have reached the point of early commercial availability. They are very different from previous optical devices, and offer opportunities that simply were not available previously. For example, the 64 × 32 S-SEED array corresponds to a chip with 2048 logic gates with 6144 logical connections (two inputs and one output per gate) or 'pinouts'. The optics to handle the necessary 16 384 light beams is within the capability of a reasonable optical system. This is quite different from conventional chips, and poses challenges as well as opportunities. The success of such devices will depend as much on innovative exploitation in novel systems as on the performance of the devices themselves.

More generally, SEEDs are examples of intimately integrated optoelectronics, where the dividing line between optics and electronics is indistinct. There is no clear separation between optics and electronics in the device structure, in its operation or even in the basic physics. As a result, we see a device that may be able to take the best advantage of both optics and electronics for the benefit of the system overall. The intimate integration between optics and electronics ensures that the interface between the two is efficient and scalable to small dimensions. As the technology becomes available, the integration of more electronic functionality may be expected, with the ultimate goal of allowing the systems designer full freedom to choose optical and electronic functions. The additional flexibility offered by layered semiconductor structures and their quantum-mechanical engineering may enable the full potential of optoelectronics to be realized.

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