

NONLINEAR OPTICS IN SEMICONDUCTORS

Optical signal processing in the future may use semiconductors in which the optical generation of electrons and holes controls the absorption and refractive index.

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The dream of the all-optical processing of information has motivated efforts over the past decade to create sensitive semiconductors that have large optical nonlinearities. Semiconductors have been the medium of choice in part because a well-developed materials technology has already been built around them. One can design semiconductor structures easily and predict their performance accurately.

The applications that have driven these studies involve the parallel processing of many bits of information, as in images. Optics is attractive here because unlike electrical signals in wires, light beams can travel through each other without interacting. Thus signals from each point of an image can simultaneously reach many points in a new plane, where one can "process" the image to enhance it or to correlate it with other images for applications such as recognizing typewritten or handwritten characters. Optical processing systems may be analog or digital, or they may use neural network architectures. Very often it is necessary for the processing element to give a nonlinear response to the optical signals. This is where nonlinear optics comes in.

One "holy grail" is a sheet of "magic material," usually conceived of as a semiconductor wafer, that will respond in a nonlinear way to light signals passing through it, ideally without any application of electrical signals. When properly configured into a device, this sheet could suddenly switch on or off, depending on the intensity of the input light, or perhaps a suitably designed device could produce a desired functional form for transmission vs incident light intensity.

To be useful, any proposed new information processing technology must compare favorably with VLSI-based digital computers and with spatial light modulators that are already in use (see the September 1989 special issue

of PHYSICS TODAY on the physics of imaging). Digital computers are usually thought to be limited to 10^4 parallel bits; nonlinear optics aims for 10^6 . Most practical spatial light modulators have millisecond response times; nonlinear optics aims for submicrosecond times.

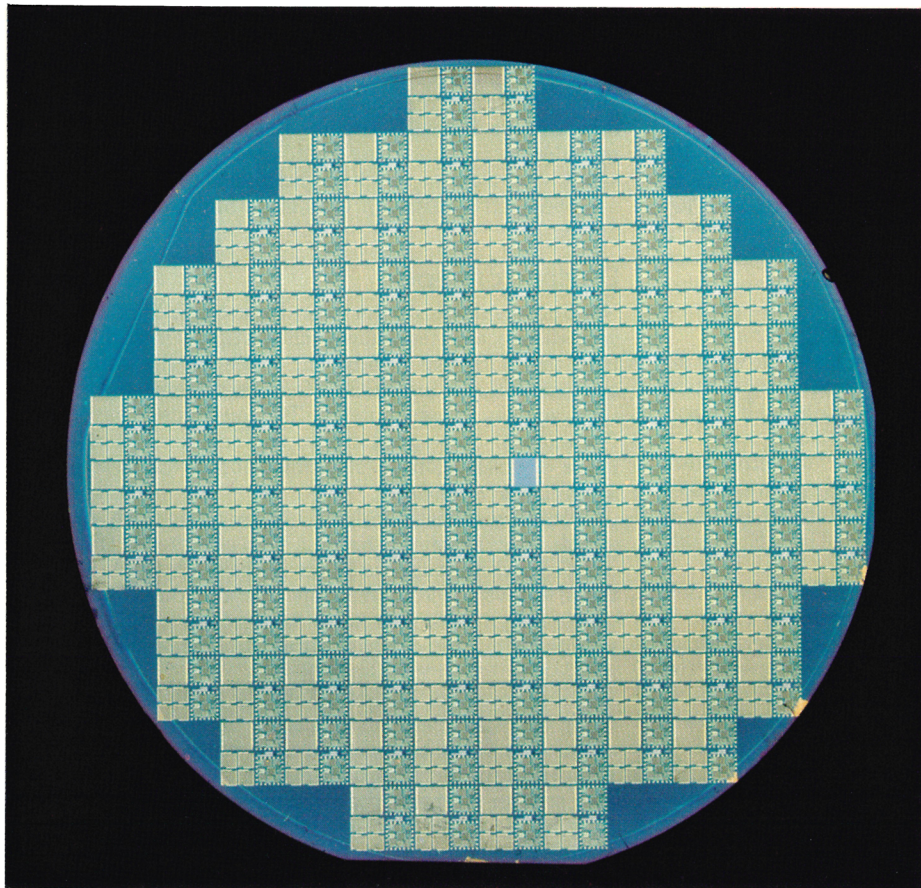
The benchmark device available today is a hybrid of optical and electrical technologies. It is the self-electro-optic-effect device, invented in 1985 by David Miller at AT&T Bell Laboratories. SEEDs have been developed to a high degree of sophistication for applications in digital parallel photonic switching. The most extensively studied device, known as the S-SEED (see figure 1), consists of two p-i-n diodes (undoped i layers sandwiched between doped n and p layers), each with multiple quantum wells in the i region, electrically connected in series. This device has already been shown to be practical in applications such as differential logic gates and memory elements that can be individually set and reset and that have complementary output logic.

The optical energy needed to switch individual SEED pixels has been measured¹ to be 4 picojoules within an active area of 5×10 microns. The device responds in the time it takes to charge the capacitance of the diodes. There is a direct trade-off between sensitivity and response time; typically 50 microwatts of power switches a single device in 80 nanoseconds. A total laser power of 2 watts would be enough to operate 10^6 parallel bits. Because the hybrid optoelectronic elements are challenging to make, nonlinear optical devices, using a suitable "magic material," would in principle be much less expensive.

The original approach: State filling

The nonlinearities in semiconductors are largest when the photon energy is just above the bandgap and some of the light is absorbed, creating free carriers. Because of the Pauli exclusion principle, the available states can fill, and the absorption will decrease with increased intensity. In semiconductors, the nonlinearities can be enhanced

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Self-electro-optic-effect

devices developed by David Miller and his coworkers at AT&T Bell Laboratories. This 3-inch-diameter GaAs wafer, fabricated with arrays of SEEDs, represents the state of the art in optoelectronic devices used for nonlinear switching. Each large square is a 64×128 array of 10-micron-wide devices (unresolved in this photo). Each of the smaller squares is a 32×64 array of devices. The patterned structures are test devices complete with the necessary bonding pads. To be used, the arrays are cleaved out of the wafer. **Figure 1**

through quantum confinement² (as Daniel Chemla describes in his article in *PHYSICS TODAY*, June 1993, page 46). Figure 2 shows some data my colleagues and I took in our laboratory at the University of Southern California on absorption as a function of photon energy in 100-Å GaAs/AlGaAs multiple quantum wells.³ The decrease, or saturation, in absorption with increasing optically induced carrier density is clearly evident.

Whenever there is a saturable absorption there will also be a saturable nonlinear refractive index, because the real and imaginary parts of the dielectric constant are related. Both nonlinearities are a function of the optically induced carrier density N . For small light levels, the absorption α and index n increase linearly with N . As the light level gets very large, both the absorption change and index change reach saturation values. Figures of merit to describe these phenomena are the respective saturation values α_s and n_s divided by the carrier density N_s required to reach halfway to saturation: $\sigma_s \equiv \alpha_s/N_s \approx d\alpha/dN$ and $\eta_s \equiv n_s/N_s \approx dn/dN$ (η_s is the refractive index change per unit of carrier density).

The nonlinear absorption and refraction due to state filling have been measured as functions of carrier density near the band edge in a number of semiconductors. The absorption and index changes α_s and n_s are typically three or four times larger in multiple-quantum-well structures than in bulk material. However, even though the exciton within the quantum well has a large figure of merit, it sits on top of a band that requires a much higher carrier density to fill. (An exciton is a quasihydrogenic atom existing because of Coulomb attraction between an electron and a hole.) As a result, multiple-quantum-well structures have figures of merit σ_s and η_s typically no

more than four times larger than those of bulk material. This finding appears to be independent of growth technology, well thickness or material.³⁻⁶ Only higher degrees of quantum confinement, such as quantum dots provide, will produce significantly higher state-filling nonlinearities. (See the June 1993 special issue of *PHYSICS TODAY* on optics of nanostructures.)

Photomodulation nonlinearities

An alternative approach that results in higher figures of merit is photomodulation of internal fields through carrier transport. Photorefractive optics researchers have known for some time that motion of photogenerated carriers within electro-optic materials can alter internal electric fields, changing the refractive index and affecting transmitted light. (See the article by Jack Feinberg in *PHYSICS TODAY*, October 1988, page 46.)

In semiconductors, the *i* layer of a *p-i-n* junction experiences an internal field. In response to this field, photogenerated carriers move and produce screening fields within the *i* regions, changing the absorption and refractive index at wavelengths near the band edge—effects usually termed electroabsorption and electrorefraction. Thus photomodulation of internal fields causes an effective nonlinearity.⁷ The photomodulation figures of merit can be much larger than those for the state-filling nonlinearities, because the electrons (and holes) travel beyond a single unit cell, enhancing the nonlinearity.

The largest effects occur when multiple quantum wells are inserted in the *i* regions of a periodically doped *n-i-p-i* structure. An internal electric field exists between the doped regions of such a structure, as the band diagram in figure 3 shows. Multiple-quantum-well structures in-

served in the *i* regions are sensitive to this field. Photo-generated carriers move within the field: Electrons fall down to the *n* regions, and holes float up to the *p* regions. The separation of carriers creates screening fields that reduce the internal field. Thus photoabsorption creates field-induced changes in absorption or refractive index within the quantum wells, resulting in self-modulation. Large optically induced absorption changes occur at very low power levels.⁸ (See figure 3.) The high sensitivity is a consequence of very long carrier recombination times, due to the spatial separation between electrons and holes. (One can shorten the recombination time, at the expense of sensitivity, by introducing recombination paths.)

The field dependence of multiple-quantum-well absorption is usually termed the quantum-confined Stark effect. It comes about because the quantum well energy levels shift with the applied field and also because the overlap between the electron and hole wavefunctions lessens with increasing field. The quantum-confined Stark effect has been the object of considerable research and is often used to make modulators. The SEED uses this effect.

Absorption in bulk semiconductors also has a field dependence, usually termed the Franz-Keldysh effect. It is much weaker than the quantum-confined Stark effect, but it has been shown to be useful in bulk photorefractive devices. Over much of the useful range of these effects, it is often sufficient to describe electroabsorption and electrorefraction as quadratic with the internal field.⁹⁻¹¹

One can estimate figures of merit for photomodulation nonlinearities by calculating the absorption and refractive index changes due to the photoinduced screening of internal fields. Referring to figure 3, the screening field between the *n* and *p* layers depends on the total photocharge separated, which is proportional to the thickness of the absorbing multiple-quantum-well structure within each layer. However, for a given internal voltage drop, the field is inversely proportional to the distance between the *n* and *p* regions. These two effects cancel, and the figure of merit depends only on the fraction Γ of the material that is filled with quantum wells and on the internal voltage drop V . All other geometric factors also cancel out, so that the figure of merit is

$$\sigma_Q \approx \alpha_Q / N = AV (e / \epsilon) \Gamma \quad (1)$$

Here A is the electroabsorption parameter, given by $\alpha_Q = AE^2$, where E is the internal field; e is the electron charge; and ϵ is the dielectric permittivity.

Similar analysis applied to η_Q , the refractive index change per unit of carrier density, results in a similar dependence on V and Γ . Typical numbers for GaAs/AlGaAs and strained InGaAs/GaAs multiple-quantum-well structures show an order-of-magnitude improvement in the figures of merit when one uses photomodulation

rather than state-filling nonlinearities. Because the figures of merit are proportional to voltage, one can obtain further enhancement by separately contacting the *n* regions and the *p* regions and imposing an external back-bias voltage between them. Estimates are that photomodulation nonlinearities could offer up to 50 times more sensitivity than state-filling nonlinearities. However, to achieve such sensitivity, care must be taken in designing devices.

Device concepts

Nonlinear semiconductors can be used in four categories of device geometries, shown schematically in figure 4. The first three involve normal incidence on the sample and are particularly interesting for two-dimensional applications such as image analysis. The fourth uses waveguides. For each of these geometries, one can use the refractive index or absorption (or a combination of these) to provide a nonlinear response.

Most measurements of nonlinearities are made in simple transmission through a slab of material (figure 4a) after absorbing substrates are removed by etching. Epitaxial growth techniques limit the thickness of a multiple-quantum-well slab to a few microns; this typically results in a poor contrast ratio (the ratio of high transmission to low transmission).

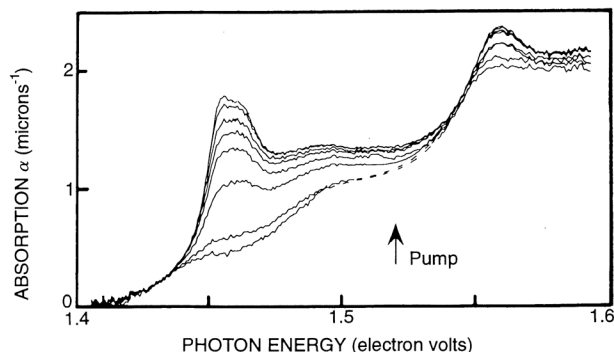
Enhancement of the nonlinear response is possible using a Fabry-Perot etalon with the mirrors placed on either side of the slab (figure 4b). When the nonlinearity is sufficiently large, optical bistability can occur; that is, at a certain intensity the transmission suddenly switches from high to low. Because of substantial absorption, the greatest switching of contrast in nonlinear etalons occurs in the reflected beam of an asymmetric cavity, in which the two mirrors have different reflectivities.

In other applications two coherent beams, incident at an angle on the slab, create an optical standing wave in the sample, making wave mixing possible (figure 4c). Photorefractive experiments in semi-insulating semiconductors use this geometry. It also can provide background-free signals through four-wave mixing.

The fourth geometry (figure 4d) features waveguides, which can be used in integrated optics applications.

Required device length

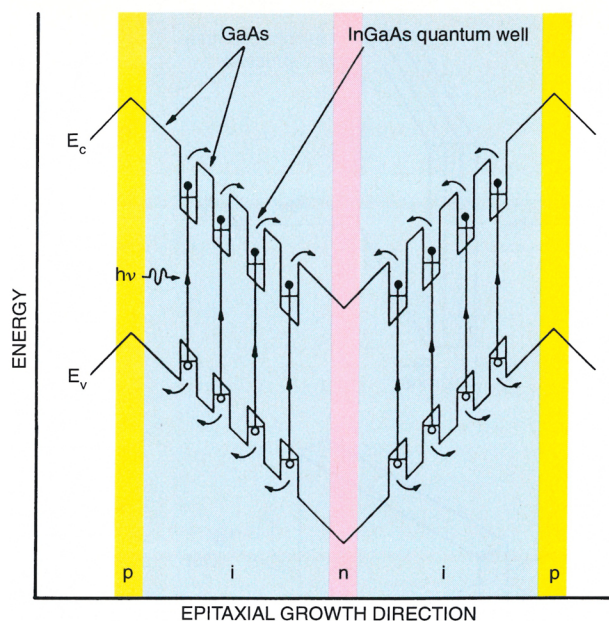
Because the nonlinear refractive index saturates, a second important figure of merit is the minimum required device length. For working nonlinear refractive devices, a significant fraction of the 2π phase changes must be optically induced within the active multiple-quantum-well medium. In nonlinear devices measured to date, $n_s < 0.02$, so that practical refractive devices operated at normal incidence and not using a high-reflectance Fabry-Perot etalon would require multiple-quantum-well lengths greater than 20



Nonlinear absorption due to state filling in 100-Å GaAs quantum wells with AlGaAs barriers. Quantum confinement produces sharp absorption features that are bleached by photoexcitation. The excitonic states fill before the conduction band states, which require higher photon fluences before their absorption saturates. This nonlinear absorption change produces a nonlinear refractive index; both effects have been used in nonlinear photonic devices. The experimental data were taken after a picosecond pump pulse had excited a known number of photocarriers. The carrier density ranges from less than $5 \times 10^{15}/\text{cm}^3$ (top curve) to $1.7 \times 10^{18}/\text{cm}^3$ (bottom curve). (Adapted from ref. 3.) **Figure 2**

Photomodulation nonlinearities in an n-i-p-i structure containing multiple quantum wells within the i region.

Top: Band diagram for the structure. Bottom: Experimental results. The conduction and valence bands E_c and E_v are tipped in physical space because of the periodic delta doping (extremely thin, highly doped n and p regions). The resulting internal field causes photogenerated carriers to separate, partially screening the internal field and modulating the absorption. The rise in peak absorption occurs as the internal field is optically decreased with increasing power. (Adapted from ref. 8.) **Figure 3**



microns. Because crystal growth techniques typically limit structures to a few microns, normal-incidence devices commonly use Fabry-Perots to reduce required multiple-quantum-well length.

Waveguides or thick bulk media usually must be shorter than the absorption length $1/\alpha$, resulting in an important figure of merit for refractive devices:

$$M \equiv n_s k / \alpha > f 2\pi \quad (2)$$

Here f is the fraction of 2π phase changes required for proper device operation. This device figure of merit M increases at wavelengths below the bandgap; however, n_s decreases at the same time, with a resulting decrease in the material figure of merit η_s . Thus designing a suitable nonlinear optical device requires a trade-off between these two figures of merit.

For absorptive nonlinearities, the applicable figure of merit is the fractional absorption change $\delta\alpha/\alpha$, which must be as large as possible. An asymmetric Fabry-Perot etalon is often used as a reflector to increase the contrast ratio. In this case the maximum reflectivity change δR is $(\delta\alpha/\alpha)^2$.

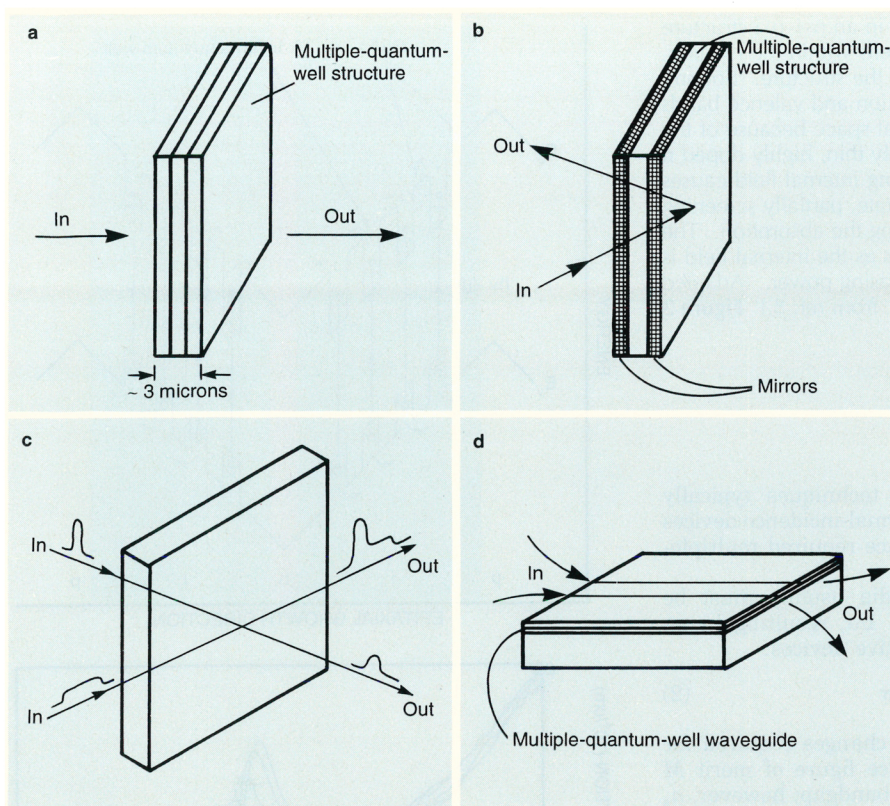
One can use the figures of merit σ_s and η_s to estimate power requirements in practical devices, relating the photogenerated carrier density to the incident intensity I and carrier lifetime τ . The largest absorptive state-filling nonlinearities typically occur in 100-Å GaAs/AlGaAs multiple-quantum-well structures, which have an operating fluence, or energy flow, $I\tau$ of $2 \mu\text{J}/\text{cm}^2$. Photomodulation nonlinearities are typically ten times more sensitive. Nonlinear refractive devices are not as sensitive as absorptive devices except when they are used in a Fabry-Perot etalon, where their operating fluence can be comparable. Even with very small pixel sizes, these fluences are much larger than electronic switching energies in complementary metal oxide semiconductor devices. Therefore nonlinear optics will be used only when optical systems have a decided advantage over electronics, as when high parallelism is required or in the ultrafast regime.

The relatively high fluences required when using localized state-filling nonlinearities can be understood if one considers that when the optical excitation is sufficient to screen the exciton fully, the conduction band is halfway to transparency. The required photocarrier density is only a few times less than that required for stimulated emission. That is, the optical excitation is typically halfway to creating a laser. To achieve more sensitive nonlinearities requires new concepts, such as photomodulation of internal fields.

The required intensity is determined by the carrier recombination time. In typical GaAs bulk and multiple-

quantum-well materials, carrier lifetimes are on the order of 20 nanoseconds, so that the required intensity for state-filling nonlinearities is $100 \text{ W}/\text{cm}^2$, low enough to be accessible with focused diode lasers. Indeed, Hyatt Gibbs's group at the University of Arizona demonstrated optical bistable switching in a GaAs Fabry-Perot etalon using a diode laser. However, achieving such intensities in a system of 10^6 parallel bits (with 10-micron pixel size) would require a 100-W laser. Because such a laser is impractical, one cannot use state filling without making the nonlinearity more sensitive by lengthening the carrier recombination time. One can do so by separating charges, as in n-i-p-i structures, where recombination times may become as long as milliseconds. In this regime state-filling nonlinearities may be practical; however, device performance slows down appreciably.

In comparing state-filling and photomodulation nonlinearities, it is important to consider that high-contrast modulation requires large fractional changes in absorption or large optically induced changes in phase. Photomodulation typically introduces smaller phase changes than state filling, and the refractive nonlinearity is often too small to be of practical use. The transmission changes induced by photomodulation typically¹² are at most 50%. In a high-contrast Fabry-Perot etalon, the maximum



Geometries in which semiconductor optical nonlinearities are used.
a: Transmission through a nonlinear slab. **b:** Asymmetric Fabry-Perot etalon, used in reflection to provide greater contrast. **c:** Wave mixing, used to provide photorefractive gain or to create new, background-free waves. **d:** Waveguide. In all cases optical control can be provided by a separate beam that illuminates the nonlinear semiconductor and is sensed by a probe beam, or by direct nonlinear response to a single beam. **Figure 4**

reflectivity change will be 0.25. Selective contacts, however, make possible maximum reflectivity changes greater than 0.5.

Recent studies have concluded that photomodulation of multiple quantum wells within n-i-p-i structures has the potential for much more sensitive nonlinearities than does state filling, given the same carrier recombination times. One can achieve even further increase by making selective contacts to the n and p regions to provide a higher voltage drop within the n-i-p-i structure. The challenge with multiple-quantum-well structures in the i regions is that photogenerated carriers can be "trapped" in the neighboring wells and not make it to the n and p regions. Theoretical estimates of possible contrast ratios have not yet been achieved in such n-i-p-i structures. It is therefore important to understand fully the transport of carriers across multiple-quantum-well structures in the presence of a field. Research in this area is still under way.

Increasing carrier lifetimes

In high-quality material, the carrier lifetime is determined by radiative recombination. One can reduce the rate of radiative recombination substantially by physically separating electrons and holes. When a suitably doped heterostructure allows electrons to collect in a different physical place than holes, the recombination time lengthens dramatically. This is the origin of the very large increase in optical sensitivity of n-i-p-i structures over undoped material.

At USC we demonstrated the lengthening of carrier recombination time and the resulting increase in nonlinear optical sensitivity in a simple thin film structure grown by the "old fashioned" technology of liquid-phase epitaxy.⁷ This device uses "localized" state-filling nonlinearities but uses carrier transport to lengthen the carrier lifetime. It

consisted of an n-type epitaxial layer grown on a semi-insulating substrate and covered with a metal film. More specifically, a single, 2-micron-thick InGaAsP layer with a band edge near 1.06 microns was sandwiched between a transparent semi-insulating InP substrate and a reflective gold layer forming a Schottky barrier.

The resulting band diagram, shown in figure 5, indicates that optically excited holes will float up out of the InGaAsP layer, while electrons will collect there. We measured a 4-microsecond lifetime for an optically induced absorption change from 53% to 78% due to state filling. This was a 200-fold increase in sensitivity over what is expected in bulk material. This example shows that even "low tech" semiconductor materials can provide sensitive nonlinearities.

The n-i-p-i structures lengthen carrier lifetimes in a similar fashion. The concept of sandwiching n and p regions, separated by i regions, to produce sensitive nonlinear optical devices was pioneered by Gottfried Dohler, working both in Germany and at Hewlett-Packard Laboratories.¹³ Quantum wells inserted into these structures to increase their nonlinear optical properties may be placed in the n and p regions (type-I n-i-p-i structures) or in the undoped i regions (type II). Photogenerated electrons fall down to the n regions, and holes float up to the p regions; the i regions keep them from recombining. Thus type-I n-i-p-i structures use state filling as the source of the nonlinearity, whereas type-II n-i-p-i's use electroabsorption. The physical separation of the carriers leads to lifetimes that can be as long as milliseconds.

The optical properties of pure n-i-p-i structures, grown without heterostructures, are complicated by the fact that absorption takes place partly in regions that experience fields and partly in regions that contain no fields. Because the optically induced absorption change is very small in pure n-i-p-i structures, optical devices usually

use type-I or type-II n-i-p-i's with heterostructures.

Considerable research has been undertaken aimed at optimizing the optically induced transmission change in n-i-p-i's with heterostructures and further enhancing the nonlinear response by placing the structure within a Fabry-Perot etalon. Experiments at the Jet Propulsion Laboratory have shown¹⁴ that an asymmetric etalon can convert a 25% transmission change due to saturable absorption into a contrast ratio of 200:1. The optimum structure, grown by molecular-beam epitaxy, used delta doping (thin layers of sheet charge grown between i regions) with two quantum wells per n region. A half-wavelength separation between successive n regions ensured that there were maxima of the standing optical wave at each well. High reflectivity resulted from distributed feedback layers that were grown as monolithic mirrors. The resulting device, operating on the basis of the state-filling nonlinearity, changed the reflectivity from 0.6% to 40% with 30 mW of optical excitation. The operating intensity was 1000 times smaller than that expected for undoped material, at the sacrifice of millisecond response times. Predictions are that this device can be the basis for 10^6 parallel bits under the control of a few hundred milliwatts of input radiation, but at speeds comparable to those in liquid crystals. The devices can be speeded up, at the cost of increased intensity requirements. Improved performance requires using type-II nonlinearities, selectively contacted. An effort in that direction continues in several laboratories.

When carriers have long lifetimes, lateral diffusion can reduce signals from finite-size illuminated spots. The conductive n and p regions enhance lateral diffusion. In practical devices one must contain carriers laterally within the optically active area by making the samples into pixels through mesa etching.

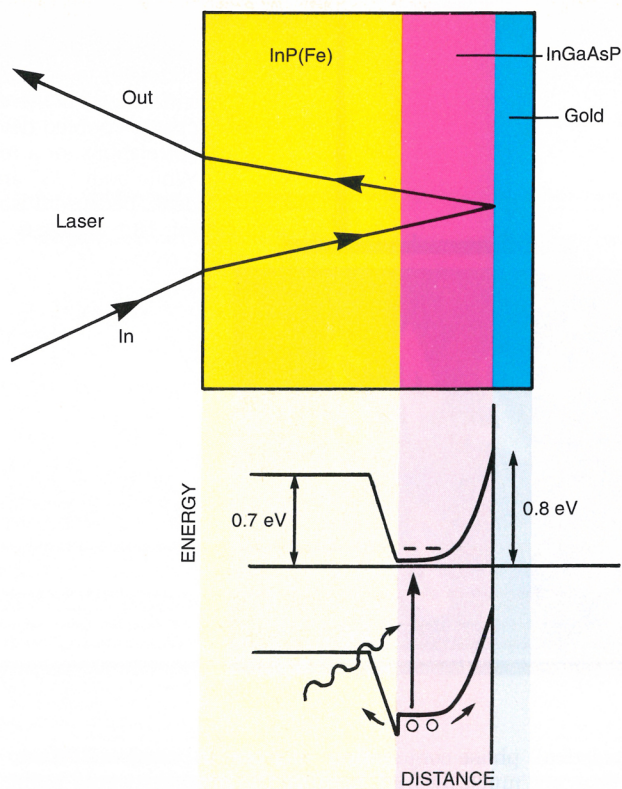
Using lateral carrier motion: Photorefractivity

Photorefractivity results from photomodulation of internal fields due to lateral carrier motion. Two coherent light waves, incident at an angle on a slightly absorbing medium, cause spatial gradients in photocarrier excitation. In suitably insulating electro-optic media, lateral motion of the photocarriers changes the internal field, thereby changing the refractive index.

In photorefractive media, photoabsorption liberates free carriers from deep traps. These carriers move laterally, undergoing a process of retrapping and reillumination until they fall into deep traps in the dark regions of the periodic optical standing wave. From there they cannot move. The gradient of charge density between the illuminated and dark regions sets up an internal electric field. Because the medium is electro-optic, a periodic refractive index results from the periodic carrier gradient.

Photorefractivity is particularly exciting because it can produce phase-conjugating mirrors. Phase conjugation is a nonlinear reflection process in which the phase is reversed, making it possible for light to travel backward through a phase-distortion medium and become undistorted on completion of a reflection path. (See Feinberg's article.)

Photorefractivity in semiconductors turns out to be a good news-bad news story. Semi-insulating III-V and II-VI semiconductors are photorefractive, because they have deep traps that can be photoactivated and because they are electro-optic. Traditional photorefractivity uses a nonresonant electro-optic index change with internal field; the resulting change is very small. Photorefractivity can be larger at wavelengths near the band edge because of the Franz-Keldysh effect. In more recent work the quantum-confined Stark effect in semi-insulating multiple



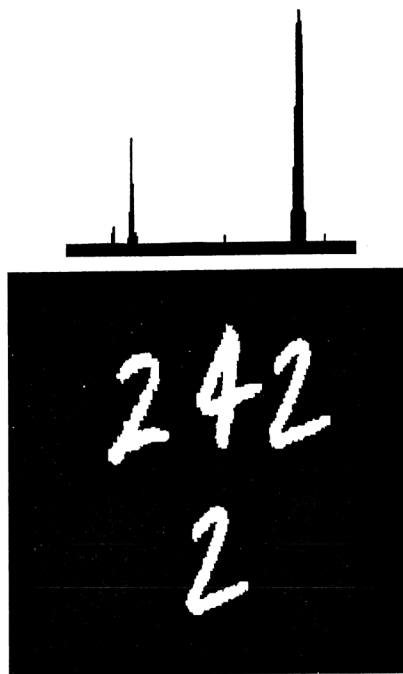
Reflective semi-insulating hetero-Schottky barrier, used as a sensitive nonlinear element operating at the Nd:YAG-laser wavelength of 1.06 microns, has the semiconductor band diagram shown at bottom (not to scale). A potential well traps electrons but not holes. The separation of photogenerated electrons and holes lengthens the carrier recombination time to 4 microseconds. (Adapted from ref. 7.) **Figure 5**

quantum wells has provided the index change.

Typical measurements are made by two-wave mixing, with one weak and one strong wave incident at angles. (See figure 4c.) The induced carrier density grating leads to an optical index grating that is no longer in phase with the optical standing wave. The out-of-phase component causes energy to couple from the strong wave into the weak wave, producing a gain on the weak beam. The gain is optimized when the carriers move laterally all the way into the dark regions. Without applied (or internal) fields, carriers move in semiconductors by diffusion and so do not become greatly separated. As a result, without relying on drift motion due to applied external fields, one measures only small gains in semiconductors.

To achieve the optimum gain—when the refractive index grating is exactly out of phase with the optical standing wave—typically requires either applying ac fields or slowly moving the optical standing wave laterally (by slowly translating a mirror in one of the beams). In InP, however, competition between electrons and thermally generated holes results in a temperature-intensity resonance that optimizes the gain without ac fields or a moving grating. Electrorefractive photorefractivity has made possible world-record gains^{15,16} in both GaAs and InP.

The large photorefractive gains inspire thoughts of



Optical image correlation. A semi-insulating multiple-quantum-well photorefractive device was used as a high-speed joint transform optical image correlator to correlate the upper row of numbers with the "2" at the bottom. The surface plot at the top of the figure is of a portion of the output of the charge-coupled device camera recording the correlation. The peaks represent correlations, or a recognition of the images. Note that the "4" is not recognized. While both "2's" are recognized, the one on the left has a smaller correlation peak, because it is not identical to the bottom "2." (Adapted from ref. 18.) **Figure 6**

practical phase-conjugating mirrors in semiconductors; these are much desired, because the gratings would build up much faster than in the commonly used barium titanate. Unfortunately, two types of effects conspire to reduce the usefulness of semiconductors in this application. The first may be called "large-signal effects." It has been shown experimentally and modeled theoretically that as the weak beam increases in intensity to become comparable to that of the strong beam, the gain decreases dramatically. The simplest explanation is that the space-charge field is clamped to the magnitude of the applied field. The reduction of gain at high modulation depths has been demonstrated both experimentally and theoretically.¹⁵

The second effect severely detrimental to semiconductor phase-conjugating mirrors is loss. Unlike with a laser, simply having a net gain is not enough to guarantee a phase-conjugating mirror. The gain must be more than twice the loss. This means that the enhanced gain near the band edge is of no value for phase-conjugating mirrors if the loss increases too much.

These two effects severely reduce the maximum possible reflectivity of a phase-conjugating mirror in a semiconductor.¹⁶ Experiments and theory have shown that higher reflectivity is possible farther from the band edge, because of reduced loss. For example, InP produces a phase-conjugating mirror of 11% reflectivity at a wavelength of 1.3 microns (far from the band edge) via the nonresonant electro-optic effect, but it produces one of less than 1% reflectivity at 970 nm via resonant electrorefraction.

One can achieve further gain enhancement by using the quantum-confined Stark effect in semi-insulating multiple-quantum-well structures instead of the Franz-Keldysh effect in bulk. Here there is a practical limit to the available slab thickness; nonetheless the index changes can be large enough that sizable effects are possible. Afshin Partovi and his coworkers at AT&T Bell Laboratories have demonstrated 3% diffraction efficiencies in a sample only 2 microns thick with 20 volts applied.¹⁷ The response time was microseconds. They have successfully used this device in an image-correlation application,

as figure 6 shows.¹⁸

This last figure is one example of the large number of optical parallel processing applications that can be made to operate efficiently using the nonlinear optical properties of semiconductors. While devices that operate on the field dependence of the absorption within multiple-quantum-well structures have the most sensitivity, further developments in the understanding of carrier motion within these structures are necessary to optimize designs for practical applications.

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