Optical Bistability in Semiconductors

DAVID A. B. MILLER, S. DES SMITH, AND COLIN T. SEATON

Abstract—Detailed results are presented on optical bistability (OB) and two-beam optical transistor (transphasor) action in simple, one-element Fabry-Perot devices, with the semiconductor InSb using a CW CO laser near the bandgap region, and OB for semiconductors in general is discussed. OB and multistability are seen in transmission and reflection at 5 K. At 77 K, $n_2 \simeq 3 \times 10^{-3}$ cm^2/W [corresponding to an effective $\chi^{(3)} \sim 1$ ESU] is measured and OB is observed at ~8 mW. Transphasor action at 5 K is presented and the influence of degenerate four-wave mixing is discussed. The basic physics of the microscopic mechanism for n_2 (bandgap-resonant saturation) is summarized and a simplified, generalized model is derived. This model and arguments on cavity optimization are used to predict order of magnitude limits to switching power, energy, and speed, both in InSb and other semiconductors, even in the absence of excitonic enhancement.

I. Introduction

RECENTLY the subject of optical bistability (OB) has received considerable attention, both theoretically and experimentally, partly because of its practical potential for laser pulse shaping, optical switching, signal processing, and memory elements. The method of achieving OB that has been most investigated experimentally involves combining a medium which displays intrinsic nonlinear refraction (intensity-dependent refractive index) with a Fabry-Perot cavity [1]-[8]. (OB due to nonlinear absorption alone in a Fabry-Perot cavity is much more difficult to observe [8].) Many of these experiments involve gases [1], [4] or liquids [3] as the nonlinear medium, but there are obvious practical advantages, from the point of view of device fabrication, in using a solid, and the first to exhibit OB was ruby [2]. To avoid the problem of finding a solid with a large intrinsic nonlinear refraction, hybrid devices, based on a synthesis of the effects of intrinsic nonlinear refraction using an electrooptic crystal combined with an electrical detector, have also been demonstrated [9].

Semiconductors, while known to exhibit comparatively large passive nonresonant $\chi^{(3)}$ [10], only received serious attention as potential materials for OB after the discoveries of strong nonlinear refraction in the region just below the optical bandgap in InSb [11] and GaAs [12]. In both materials, the effect is explained by saturation of dispersion (the same basic mechanism used in other CW observations of OB [1], [2], [8]), although the details vary; the observations in GaAs by Gibbs *et al.* [12] rely on the existence of excitons, while those in InSb [11] are ascribed to interband transitions [11], [13], excitons being absent. In both InSb [6] and GaAs [5], OB has been briefly reported and, with InSb, this has been extended to demonstrate two-beam optical transistor (transphasor) operation [7]. There are several potential advantages in using semiconductors for optically bistable devices: 1) semiconductor fabrication technology is already highly developed (indeed, the GaAs sample used for OB was prepared by molecular beam epitaxy, although with InSb only simple crystal cutting and polishing techniques have so far been required) and, thus, optical circuit integration and two-dimensional image processing systems should be possible given suitable devices; 2) semiconductor devices are small and, hence, have low calculated cavity build-up times (~1.2 and ~20 ps, respectively, for GaAs [5] and InSb [6] devices already demonstrated); 3) the observed nonlinearities (e.g., n_2, defined through $n = n_0 + n_2 I$ where I is the intensity and n and n_0 are the total and linear refractive indexes, respectively) are large ($n_2 \sim 4 \times 10^{-4}$ cm^2/W in GaAs, and as high as $\sim 3 \times 10^{-3}$ cm^2/W in InSb in measurements at 77 K reported in this paper, corresponding to an effective degenerate four-wave $\chi^{(3)}$ $(\omega : \omega, -\omega, \omega)$ ~1 ESU); 4) while switch-off times may be limited by material relaxation times, switch-on times, in principle, are not (a fact already demonstrated in GaAs [5]), and material relaxation times can, anyway, be engineered to a considerable extent by, for example, doping, particularly for the nonlinearity in InSb which is present also in impure material (as shown empirically by results in this paper on OB at 77 K). These factors combined suggest that small, low-power, low-energy, fast-switching, integrable devices may ultimately be possible with semiconductors.

In this paper we present results on optical bistability, multistability, and transphasor action in simple one-element devices made from InSb, at 5 K and 77 K. We first discuss briefly the relevant aspects of the basic physics of the proposed microscopic nonlinearity for InSb [13] (nonlinear refraction by bandgap-resonant saturation). Finally, we present simple macroscopic arguments to predict the limits on switching power, energy, and speed, and combine microscopic and macroscopic arguments to discuss scaling into other semiconductor materials at other wavelengths.

II. Nonlinear Refraction by Bandgap-Resonant Saturation in InSb

Nonlinear refraction has been reported [11], [13] in cooled InSb in the region just below the bandgap energy. Both these and the present measurements used a CW CO laser, tunable over ~60 lines between ~5.3 and 6 μm around the bandgap energy of InSb at 5 or 77 K. (At room temperature the bandgap lies outside the laser tuning range.) Although nonlinear absorption is also present in InSb, the nonlinear refraction is seen at intensities where the absorption is substantially linear [14], [15]. The nonlinear refraction is measured through the self-induced distortion (observed to be self-defocusing [15]) of an originally

Manuscript received July 30, 1980; revised November 5, 1980.

The authors are with the Department of Physics, Heriot-Watt University, Edinburgh EH14 4AS, Scotland.

0018-9197/81/0300-0312$00.75 © 1981 IEEE

Gaussian beam passed through antireflection-coated InSb crystals, and increases rapidly in strength as the photon energy approaches the bandgap at both 5 and 77 K. n_2 has been measured as $n_2 \simeq -6 \times 10^{-5}$ cm^2/W at 5 K at 1886 cm^{-1}, with an absorption coefficient of ~0.9 cm^{-1}. We report here measurement of $n_2 \simeq -3 \times 10^{-3}$ cm^2/W at 77 K at 1852 cm^{-1} (actually slightly above the nominal bandgap of ~1840 cm^{-1} at 77 K), with linear absorption of ~80 cm^{-1}, in a sample of n-type InSb, $N_D - N_A \sim 4 \times 10^{14}$ cm^{-3} and thickness 130 μm, using a 160 μm $1/e^2$ diameter beam spot size. With such large nonlinearities, optical length changes of ~$\lambda/2$ are readily observed with milliwatt laser powers.

The microscopic mechanism of this nonlinear refraction is discussed in detail elsewhere [13]; for this discussion we summarize and generalize it briefly. Each possible valence-to-conduction-band transition in unit volume makes a contribution Δn to the refractive index:

$$\Delta n \simeq \frac{2\pi}{\hbar n_0} \cdot \frac{|\mu|^2}{\omega_0 - \omega}$$

(neglecting broadening for simplicity). Here ω_0 is the center frequency of the transition, ω is the measurement frequency, and μ is the effective electric dipole moment of the transition. If such a transition is blocked by being populated (i.e., saturated), the refractive index at ω is reduced by Δn. Optical absorption in the semiconductor creates populations, thus blocking transitions and altering the refractive index. Semiconductors are particularly suitable for photon energies at or below the bandgap energy because, then, nearly all the states which can be populated have center frequencies above the radiation frequency, and so there is no cancellation in the change in the refractive index because all Δn have the same sign. Even in the region below the bandgap energy there is finite absorption into these states, assisted by scattering events (e.g., optical phonon scattering), although the scattering mechanisms may vary with temperature and material. The problem with any detailed theory for a semiconductor lies in knowing precisely what the distribution of excited populations is between the various possible states of different ω_0 (and even precisely what those states are), requiring detailed knowledge of the absorption and scattering mechanisms and state lifetimes.

However, we can at least assign effective average coefficients in a simple description. We expect the total change in the refractive index $\delta n = \sigma N$ where N is the total induced population and σ, defined as the refractive index change for one excited system per unit volume, is

$$\sigma \simeq \frac{2\pi}{\hbar n_0} \cdot \frac{|\bar{\mu}|^2}{(\bar{\omega}_0 - \omega)}$$

where $|\bar{\mu}|^2$ and $\bar{\omega}_0$ are effective average values. N is determined by an elementary rate equation with a generation rate = $\eta \alpha I/\hbar\omega$ and an averaged relaxation rate N/τ. Here η ($\lesssim 1$) is the quantum efficiency of excitation and α is the absorption coefficient. Thus, in the steady state, the approximate relation describing n_2 is

$$n_2 \simeq \frac{\eta\sigma\alpha\tau}{\hbar\omega}.$$

In InSb we take the effective matrix element as being that for ordinary (heavy hole) valence-conduction band direct transitions and do not include any excitonic resonance enhancement (introduced empirically for GaAs [12]), exciton resonance being absent, anyway, in InSb without a magnetic field. For this transition in many semiconductors $|\mu|^2 \simeq \frac{1}{3}(eP/\hbar\omega)^2$, and with $mP^2/\hbar^2 \sim 11$ eV (1.7×10^{-11} ergs) and $n_0 \simeq 4$ in InSb, a value of $\sigma \sim 5 \times 10^{-18}$ cm^{-3} is predicted for $\hbar\bar{\omega}_0 - \hbar\omega \sim \hbar\bar{\omega}_0/100$ (i.e., ~20 cm^{-1} for InSb near the bandgap) and, therefore, $n_2 \sim 5 \times 10^{-5}$ cm^2/W for $\alpha \sim 1$ cm^{-1}, $\eta \sim 1$, and $\tau \sim 300$ ns, in order of magnitude agreement with experimental results at 5 K. Similar agreement is obtained for 77 K results with $\alpha \sim 80$ cm^{-1} and $\hbar\bar{\omega}_0 - \hbar\omega \equiv \sim 50$ cm^{-1} ($\equiv$ kT at 77 K), giving $\sigma \simeq 2 \times 10^{-18}$ cm^{-3}. This simple generalized model is especially useful for scaling this mechanism to other semiconductors; this will be discussed in Section IV.

III. Observations of Optical Bistability and Transphasor Action in InSb

The strong microscopic nonlinearity discussed in the previous section suggests that optical bistability should be readily observed with cooled InSb. The experimental situation is complicated in several ways when compared to the simple theory [16] for the plane-parallel lossless Fabry-Perot containing a medium with a $\chi^{(3)}$ nonlinearity. 1) There is inescapable linear (and also some nonlinear) absorption in InSb. 2) The system will generally be illuminated with a Gaussian, rather than uniform, profile beam. 3) The nonlinearity itself may saturate, thereby departing from $\chi^{(3)}$ behavior. 4) There may also be some diffusion of excitation (i.e., carrier diffusion), resulting in nonlocal behavior of the nonlinearity and a further breakdown of a $\chi^{(3)}$ description. A theory including linear absorption and discussing the resulting optimum cavity design has been developed [17]. The effect of Gaussian profiles has been considered for some specific cases with a self-focusing nonlinearity [16], and Gaussian beam effects have recently been analyzed for some other conditions [8], but no general theory of the effect of Gaussian beams has so far been presented. Again, no general theory exists for the effect of saturation of the nonlinearity itself, neither is this saturation known in advance empirically or theoretically, with any accuracy, for InSb. The effects of diffusion have also not been modeled, although one simple consequence of even quite weak diffusion is that standing wave effects in the nonlinear response tend to average out, leading to a reduction of up to 1.5 in the effective nonlinear response for a given incident intensity [16]. These various unknown factors make any detailed comparison of theory and experiment impossible, at present, for InSb. Indeed, for example, it is not even intuitively clear in advance whether optical bistability should exist at all for Gaussian beam illumination. However, we have been able to demonstrate optical bistability in InSb with very simple systems.

Using the CW CO laser, nonlinear Fabry-Perot action and bistability are observed (Figs. 1-3) under CW conditions with the beam power controlled by a continuously variable attenuator system [18] designed to maintain a constant input beam shape, regardless of beam power. All the powers in these results were measured with slow response (~1 s) pyroelectric detection

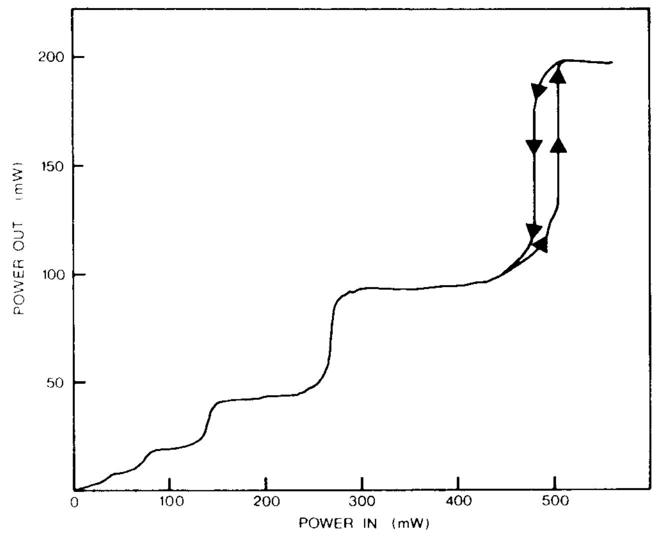


Fig. 1. Transmitted power plotted against incident power for a CW CO laser beam (wavenumber 1895 cm^{-1}, spot size ~180 μm) passing through a polished plane-parallel InSb crystal [5 × 5 mm × 560 μm thick, $N_D - N_A \sim 3 \times 10^{14}$ cm^{-3} (n-type)] at ~5 K.

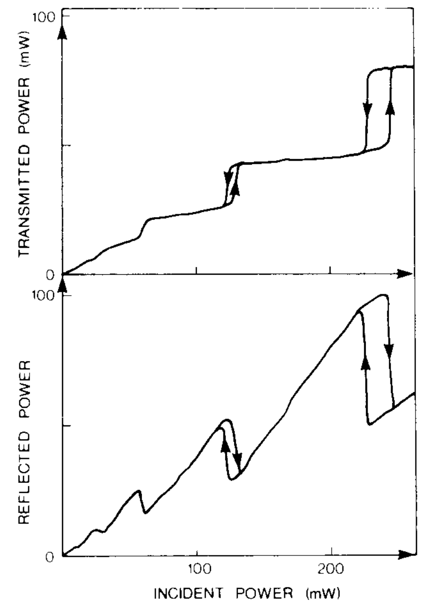


Fig. 2. Transmitted and reflected power plotted against incident power. Sample, beam, and temperature are similar to those for Fig. 1. Detuning is adjusted for optimum performance.

systems. The sample is held in a cryostat that can be filled with liquid helium or nitrogen. The results taken at ~5 K all used a natural reflectivity crystal of InSb. Because of the large refractive index of InSb (~ 4), this gives an ~36 percent reflection per face, so Fabry-Perot action can be seen in a plane-parallel polished crystal without further mirrors or reflection coatings, although this will have low finesse. When the effects of linear absorption (~ 50-60 percent per pass) are included, the effective reflectivity R_α is ~18-14 percent and a calculated plane-wave finesse $\mathcal{F}$ $(\equiv \pi\sqrt{R_\alpha}/(1 - R_\alpha))$ is 1.6-1.4. The measured finesse of the system (derived from observations of the contrast between high and low transmission using a Gaussian beam) was ~1.1 at the wavelength used in the experiments. Clear, nonlinear Fabry-Perot action is seen (see Fig. 1). Each of the successive kinks in the curve is attributed to successive alterations of ~λ/2 in the effective cavity length. The rising edges of the "steps" in the characteristic in Fig. 1 exhibit differential gain, the "flat steps" show limiter action, and clear bistability is finally seen in the fifth nonlinear interference order. These observations are the first reported to show multiple nonlinear interference orders in a nonthermal intrinsic device, and, consequently, the first to show bistability in such high order and with such low finesse. It is a general qualitative property of the solutions for refractive bistability [16], [17] that bistability should become progressively easier to observe at a higher nonlinear interference order. We estimate that bistability should be observable in the second nonlinear order with such a cavity; the observation of bistability in only the fifth order in Fig. 1 may be due either to the use of the Gaussian beam (in Fig. 1 *all* the transmitted power is measured—there is no sampling of one particular part) or to instabilities in the laser or in the cavity tuning which wash out the bistability in these slow-response observations. (The cavity can be "tuned" by moving the crystal from side to side, since the crystal faces are only parallel to within ~1 mrad.) Another obvious feature of Fig. 1 is that successive nonlinear interference orders correspond to successively larger increments of intensity. Qualitatively, this can be explained in either of two ways: 1) the beam is defocusing significantly inside the crystal; 2) the nonlinearity itself is saturating. We believe 1) to be unlikely for the following reason: even with a 5λ/2 (i.e., ~3 μm) phase lead in the center of the beam, the resulting angle of expansion for a beam with a radius of ~100 μm is only ~3/100; in a crystal of ~500 μm thickness, even with ~2 complete roundtrips, the resulting increase in beam radius is ~30 μm, giving a reduction of $(1/1.3)^2$, ~40 percent, in intensity. Since the separation between the fourth and fifth orders is ~5 times as large as that between the first and second, we discount this mechanism as the cause of this effect, and ascribe this, instead, to saturation of the nonlinear refraction. While detailed comparison of theory and experiment is not possible, the nonlinear refraction at low intensities deduced from Fig. 1 ($n_2 \sim 3 \times 10^{-5}$ cm^2/W) is in reasonable agreement with other measurements [15].

We have also been able to observe (in another sample of InSb) multiple bistable regions in successive orders and to demonstrate bistability and differential gain in reflection (see Fig. 2). To observe the reflected power, the input beam is incident at a slight angle to the sample face so that the reflected beam can be detected separately. Both transmitted and reflected powers are high, up to ~50 percent of the incident power in both cases, with peak reflection actually higher than peak transmission, demonstrating potentially greater efficiency for reflective operation of such devices. The existence of multiple bistable regions in refractive bistability is to be expected theoretically, and this experimental result demonstrates the possibility of intrinsic multistable optical devices.

The original observation of self-defocusing in InSb showed strong effects at 5 and 77 K [11], and the further measurement at 1852 cm^{-1} and 77 K, reported in the preceding section of this paper, suggests that optical bistability should be observable at 77 K also. To demonstrate this, we used a ready-polished slice of inexpensive polycrystalline InSb of the kind normally used as a monochromator order-blocking filter and coated it

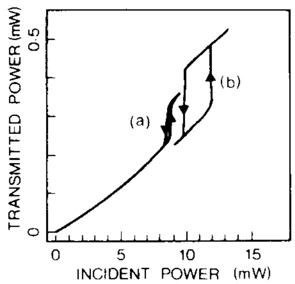


Fig. 3. Transmitted power plotted against incident power for CW CO laser beam (wavenumber 1827 cm^{-1}, spot size ~150 μm) passing through a polished polycrystalline InSb slice (5 × 5 mm × 130 μm thick) coated to ~70 percent reflectivity on both faces, held at ~77 K. Onset of bistability is seen at ~8 mW [trace (*a*)] with clear bistability at slightly higher powers with different cavity detuning [trace (*b*)].

on both faces with a simple two-layer Ge and ZnS 70 percent reflecting coating. The resulting optical bistability with the InSb cooled to 77 K is shown in Fig. 3. With the slightly higher finesse cavity (measured with the Gaussian beam as ~3), optical bistability is now seen in the first order. The critical power for the onset of bistability [trace (*a*)] is seen to be ~8 mW. Detuning the cavity slightly [trace (*b*)] produces clear bistability at slightly higher powers. (The cavity is again tuned by moving it across the beam.) The overall transmission is low for this cavity, largely because the cavity is thicker than the optimum [17]. No attempt has been made in either the 5 or 77 K results to optimize cavity design, and considerable reductions are to be expected in switching powers, as will be discussed in the next section. While the effect of the Gaussian beam is not fully understood, one empirical consequence observed in all our bistability results is that the transmitted laser beam profile, which (observed in the far field) shows a ring structure similar to that observed without Fabry-Perot action [11], [15], changes discontinuously at the bistability transitions.

The 77 K device has also been observed dynamically. Using an electrooptic modulator to sweep the beam power up and down across the width of the bistable region at a relatively slow sweep rate (~1 kHz), the transmitted power is seen to switch rapidly on and off at the bistable transitions. Switch-on and switch-off occur in $\lesssim$500 ns, although accurate measurements of switching cannot be made at present due to slow detector and amplifier response times.

The observation of differential gain in the results of Fig. 1 suggests that this can be used to give some sort of "optical transistor" action. This must be interpreted with care, as differential gain refers only to amplification of fluctuations in *one* beam; any true "optical transistor" must use *two* beams, with small changes in one beam used to produce larger changes in another. The distinction is not trivial. Inside a Fabry-Perot cavity there are counterpropagating beams, due to the reflections, even for only one input beam. With only one beam the behavior in the presence of a third-order nonlinearity [$\chi^{(3)}$ $(\omega:\omega, -\omega, \omega)$ or n_2] is adequately described by phase changes due to nonlinear refraction. However, as soon as another beam at the same frequency is introduced into the cavity, the physics alters as the conditions for degenerate four-wave mixing (DFWM) are satisfied and power is transferred between the various beams and new beams generated. This has been observed in InSb [19] at power levels comparable to or lower than those used here for bistability. DFWM should therefore have a strong effect on any true "optical transistor" action in intrinsic nonlinear Fabry-Perot devices; it is certainly not valid to assume "optical transistor" action on the basis of single-beam differential gain observations. We have directly demonstrated [7] "optical transistor" action in an InSb nonlinear Fabry-Perot device (see Fig. 4). These results were taken under similar conditions to those of Fig. 1, with the peaks in Fig. 4 corresponding to the rising edges of the "steps" in Fig. 1. However, now two beams are coincident on the sample at slightly different angles, a main beam and a weak beam. The gain is the ratio of changes in transmitted main beam power to changes in incident weak beam power. Real signal gains >1 at the second-, third-, and fourth-order transitions are clearly observed. The simplest view of the operation of the device is that the weak beam induces a small change in the phase thickness of the cavity which is transferred into the main beam, and, hence, by analogy with the electrical transistor, we term this device a "transphasor." We have been able to observe signal gain not only with the two beams derived from one laser, but also by using two different CO lasers.

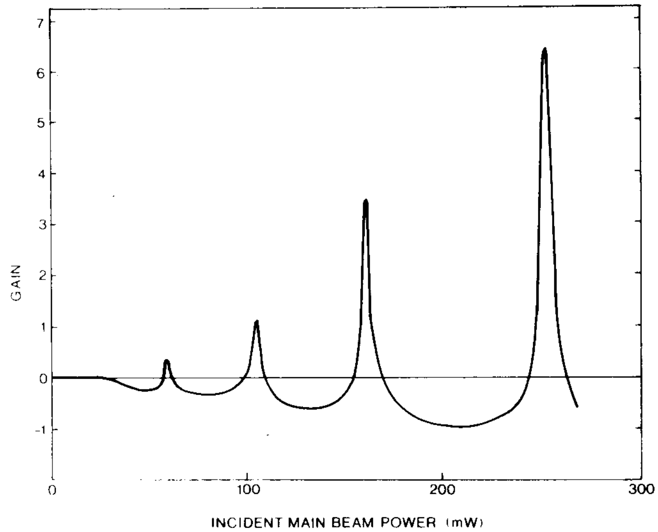


Fig. 4. Transphasor gain (see text) plotted against main beam power. Sample, beams, and temperature are similar to those for Fig. 1.

(Note that the effects of DFWM are not to be expected for any analogous hybrid devices [9], as DFWM depends on a "grating" response in the medium not synthesized in hybrid operation.)

IV. Limits on Optical Bistability in Semiconductors

In the observations discussed in this paper, no attempt has been made to optimize devices in switching power, energy, speed, or size. Using absorbing Fabry-Perot cavity optimization analysis [17] and elementary physics, measured values can be scaled to indicate the limits to device operation both in InSb and in other semiconductor materials using the same nonlinearity.

Diffraction imposes limits on device area d^2; the fundamental limit due to diffraction on the spot area in a medium of refractive index n is $d^2 \gtrsim (\lambda/n)^2$, although, in practice, this could only be used in a guided wave structure because diffraction inside an open cavity will spoil the cavity finesse as soon as the effective distance D_F, traveled by the beam inside the cavity, exceeds the diffraction length. In an absorbing Fabry-Perot, a simple upper limit on D_F is the absorption length α^{-1}; for the optimized cavity design [17] (mirror transmissivity $1 - R =$ absorption per pass A), $D_F \simeq \alpha^{-1}$. Thus, for an open cavity, $d^2 \gtrsim \lambda/\alpha n$.

Minimum switching energy is limited by the energy required to create a sufficient refractive index change δn in the device volume for switching. Using the $1 - R = A$ design [17], $\delta n \gtrsim \lambda/(2\sqrt{3}\,\mathcal{F} l)$ for cavity length l and finesse $\mathcal{F}$. Since $\eta\sigma$ is the refractive index change for one absorbed photon per unit volume, the minimum *absorbed* energy for switching is $E_{\text{abs}} \simeq hcd^2/(2\sqrt{3}\eta\sigma\mathcal{F})$. For $1 - R = A$, between $\frac{1}{8}$ and $\frac{1}{2}$ of the *incident* energy E_{inc} is absorbed [17], varying with tuning between the critical mistuning and the resonance condition, respectively, giving $E_{\text{inc}} \gtrsim 4\,E_{\text{abs}}$ for switching.

If the relaxation of the excitation in the semiconductor is approximated by a single relaxation time τ, then the resulting rate equation for the excited population (and, hence, the refractive index) becomes analogous to the Debye relaxation equation used in the transient analysis of Bischofberger and Shen [3], so their results should apply to this case, giving switching times of $\sim\tau$ when operating near the steady-state holding intensity, provided switching is not already limited by cavity field built-up time [3] τ_c. An upper limit on τ_c is the time taken to propagate a distance α^{-1} in the material $n/\alpha c$; for the $1 - R = A$ design, $\tau_c \simeq n/\alpha c$. When the device is switched on by a pulse of instantaneous power much greater than the holding power, switch-on time should, of course, drop to the time taken to absorb the switching energy (provided this is greater than τ_c).

The steady-state operating power P_{inc} for optimized devices can be estimated from the critical intensity for the onset of bistability I_c [17], and the device area is $P_{\text{inc}} \simeq d^2 I_c \simeq 4d^2hc/(\sqrt{3}\eta\sigma\tau\mathcal{F})$ (where the additional possible reduction of $\frac{2}{3}$ due to standing wave effects is neglected).

Taking the extreme case of a guided wave cavity of area $(\lambda/n)^2$ with $\mathcal{F} = 100$ for InSb with $\eta\sigma \gtrsim 2 \times 10^{-18}$ cm^{-3} at 77 K for 1852 cm^{-1}, gives a minimum absorbed switching energy $E_{\text{abs}} \sim 0.5$ fJ. Alternatively, for a more modest open cavity design with $\alpha \sim 80$ cm^{-1} (as measured for InSb at 77 K for 1852 cm^{-1}), which allows d to be as small as ~ 20 μm, a finesse $\mathcal{F}$ of 30 (corresponding to $R = 95$ percent, $A = 5$ percent), a thickness of 6 μm, and $\tau_c \sim 1.7$ ps, the predicted minimum incident energy for switching is $E_{\text{inc}} \sim 1$ pJ, leading to subnanosecond switch-on times for milliwatt powers. fJ switching energy has also been predicted for GaAs on the assumption that an $\sim(0.2\ \mu\text{m})^3$ volume can be made to switch [20], and fast turn-on with pulsed illumination has already been seen in GaAs [5].

The operating power P_{inc}, the speed of switch-off, and the speed of switch-on under low intensity illumination depend on τ. While the bulk recombination time can be long for cooled InSb (e.g., $\sim$300 ns), it is not an intrinsic property of the material. By altering doping levels, radiative and Auger recombination can shorten this substantially; for small devices, surface recombination and diffusion may dominate, anyway, and intraband relaxation can also contribute to nonlinear refraction, since the change in the refractive index is sensitive to the energy distribution of excitation. Diffusion time constants are proportional to $\sim d^2$ and, for $d \sim 5$ μm, values of $\tau \sim 1$ ns can be calculated for InSb at 77 K from mobility data. However, even for $d \sim 100$ μm, where diffusion is negligible, with $\mathcal{F} = 30$, $P_{\text{inc}} \sim 250$ μW can be predicted. The above arguments, in general, predict lower switching energies and faster responses from smaller devices.

It is the large change in the refractive index per absorbed photon per unit volume $\eta\sigma$ discussed in Section II which makes InSb interesting for optical bistability. This, in turn, is due to: 1) a large effective electric dipole matrix element, and 2) good resonance with the excited systems due to operating near or just below the bandgap energy. The matrix element μ for interband transitions is large in InSb due to a scaling which applies in all III-V semiconductors and many others, which makes $\mu \propto 1/\omega$ because the P matrix element (see Section II) is essentially constant from semiconductor to semiconductor; InSb, having a narrower gap, therefore has a large μ for states near the bandgap energy. Since $\eta\sigma \propto \mu^2$, we expect a fall-off of $\eta\sigma \propto 1/\omega^2$ in going to wider gap materials. One way around this is to attempt to use excitonic transitions, as has been done by Gibbs *et al.* in GaAs [5], where the effective matrix element is greatly enhanced by coulombic correlation of the electron and hole wave functions, although this correlation can be "washed out" by impurities or thermal effects at higher temperatures. By contrast, the basic interband effect utilized in InSb is not, in principle, destroyed by either impurities or temperature and should also be present at room temperature, although the resonance may be weaker due to the greater thermal energy spread of excited carriers. The basic $1/\omega^2$ fall-off should, however, be compensated by the fact that diffraction limits enable tighter focusing by a factor of $1/\lambda^2$ in intensity for a given power. At shorter wavelengths the corresponding change in cavity length to switch the device is shorter by a factor $\propto \lambda$, but this is exactly compensated, in predicting switching intensities, by the fact that the photon energy is correspondingly larger. These arguments are, therefore, encouraging for the use of other semiconductor materials for optically bistable devices, even in the absence of excitonic enhancement. One practical point which may cause problems in other materials and at higher temperatures is the existence of thermal effects, already observed in GaAs [5].

V. Conclusions

We have been able to demonstrate differential gain, limiter action, optical bistability, multistability, and transphasor (optical transistor) action in simple, one-element, low-finesse, low-power, InSb Fabry-Perot devices with small active volumes at both 5 and 77 K. We have developed a simplified and generalized theory of the proposed microscopic mechanism (nonlinear refraction by bandgap-resonant saturation), both to clarify the basic physical principles and to enable simple order-of-magnitude scaling calculations. The measured values of materials parameters (including new measurements presented here for 77 K) are shown to agree well with theory. The physics of the lower limits on switching power, energy, and speed have been discussed and simple relations derived. Projected switching powers are well within the range of powers attainable with, for example, laser diodes. Based on measured values for InSb at 77 K we are able to predict incident switching energies of ~1 pJ in an open Fabry–Perot cavity, with fundamental limits in a guided wave device (such as might be used in an integrated optical circuit) $\lesssim 1$ fJ absorbed energy. Subnanosecond switch-on times are predicted for milliwatt laser powers. While switch-off times are liable to depend on material relaxation, these should be faster for smaller devices. These predictions can only be regarded as approximate, but they demonstrate the basic scale of limitations in these devices. From scaling arguments to other semiconductor materials at other wavelengths, we conclude that because of the compensating effects of weaker nonlinearity but stronger focusing, shorter wavelength operation should be possible; the basic nonlinearity discussed in this paper is also not expected to disappear at higher temperatures so that room temperature operation remains a possibility at present.

In general, therefore, we believe that the development of semiconductor nonlinear Fabry–Perot devices may lead to many useful applications in optical switching and laser pulse shaping.

Acknowledgment

The authors are grateful to B. S. Wherrett for many useful discussions, and A. M. Johnston for experimental assistance.

References

[1] H. M. Gibbs, S. L. McCall, and T.N.C. Venkatesan, "Differential gain and bistability using a sodium-filled Fabry–Perot interferometer," *Phys. Rev. Lett.*, vol. 36, pp. 1135–1138, 1976.

[2] T.N.C. Venkatesan and S. L. McCall, "Optical bistability and differential gain between 85 and 296°K in a Fabry–Perot containing ruby," *Appl. Phys. Lett.*, vol. 30, pp. 282–284, 1977.

[3] T. Bischofberger and Y. R. Shen, "Transient behaviour of a nonlinear Fabry–Perot," *Appl. Phys. Lett.*, vol. 32, pp. 156–158, 1978;——, "Theoretical and experimental study of the dynamic behaviour of a nonlinear Fabry–Perot interferometer," *Phys. Rev. A*, vol. 19, pp. 1169–1176, 1979.

[4] D. Grischkowsky, "Nonlinear Fabry–Perot interferometer with subnanosecond response times," *J. Opt. Soc. Amer.*, vol. 68, pp. 641–642, 1978.

[5] H. M. Gibbs, S. L. McCall, T.N.C. Venkatesan, A. C. Gossard, A. Passner, and W. Wiegmann, "Optical bistability in semiconductors," *Appl. Phys. Lett.*, vol. 35, pp. 451–453, 1979.

[6] D.A.B. Miller, S. D. Smith, and A. Johnston, "Optical bistability and signal amplification in a semiconductor crystal: Applications of new low-power nonlinear effects in InSb," *Appl. Phys. Lett.*, vol. 35, pp. 658–660, 1979.

[7] D.A.B. Miller, S. D. Smith, and A. Johnston, "Two beam optical signal amplification and bistability in InSb," *Opt. Commun.*, vol. 31, pp. 101–104, 1979.

[8] R. J. Bullough, J. Cooper, M. W. Hamilton, W. J. Sandle, and D. M. Warrington, "Optical bistability in a Gaussian cavity mode," in *Proc. Int. Conf. Workshop Opt. Bistability*. New York: Plenum, to be published.

[9] P. W. Smith and E. H. Turner, "A bistable Fabry–Perot resonator," *Appl. Phys. Lett.*, vol. 30, pp. 280–281, 1979; P. W. Smith, E. H. Turner, and P. J. Maloney, "Electrooptic nonlinear Fabry–Perot devices," *IEEE J. Quantum Electron.*, vol. QE-14, pp. 207–212, 1978; P. W. Smith, I. P. Kaminow, P. J. Maloney, and L. W. Stulz, "Integrated bistable optical devices," *Appl. Phys. Lett.*, vol. 33, pp. 24–26, 1978;——, "Self-contained integrated bistable optical devices," *Appl. Phys. Lett.*, vol. 34, pp. 62–65, 1979.

[10] C. Flytzanis, "Theory of nonlinear optical susceptibilities," in *Quantum Electronics*, vol. 1A, H. Rabin and C. L. Tang, Eds. New York: Academic, 1975, pp. 9–207.

[11] D.A.B. Miller, M. H. Mozolowski, A. Miller, and S. D. Smith, "Nonlinear optical effects in InSb with a cw CO laser," *Opt. Commun.*, vol. 27, pp. 133–136, 1978.

[12] H. M. Gibbs, A. C. Gossard, S. L. McCall, A. Passner, W. Wiegmann, and T.N.C. Venkatesan, "Saturation of the free exciton resonance in GaAs," *Solid State Commun.*, vol. 30, pp. 271–275, 1979.

[13] D.A.B. Miller, S. D. Smith, and B. S. Wherrett, "The microscopic mechanism of third-order optical nonlinearity in InSb," *Opt. Commun.*, vol. 35, pp. 221–226, 1980.

[14] D.A.B. Miller, Ph.D. dissertation, Heriot-Watt Univ., Edinburgh, Scotland, 1979, unpublished.

[15] D. Weaire, B. S. Wherrett, D.A.B. Miller, and S. D. Smith, "Effect of low-power nonlinear refraction on laser-beam propagation in InSb," *Opt. Lett.*, vol. 4, pp. 331–333, 1979.

[16] F. S. Felber and J. H. Marburger, "Theory of non-resonant multistable optical devices," *Appl. Phys. Lett.*, vol. 28, pp. 731–733, 1976; J. H. Marburger and F. S. Felber, "Theory of a lossless nonlinear Fabry–Perot interferometer," *Phys. Rev. A*, vol. 17, pp. 335–342, 1978.

[17] D.A.B. Miller, "Refractive Fabry–Perot bistability with linear absorption: Theory of operation and cavity optimization," this issue, pp. 306–311.

[18] D.A.B. Miller and S. D. Smith, "Variable attenuator for Gaussian laser beams," *Appl. Opt.*, vol. 17, pp. 3804–3808, 1978.

[19] D.A.B. Miller, R. G. Harrison, A. M. Johnston, C. T. Seaton, and S. D. Smith, "Degenerate four-wave mixing in InSb at 5 K," *Opt. Commun.*, vol. 32, pp. 478–480, 1980.

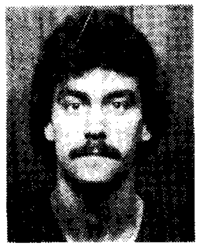
[20] H. M. Gibbs, S. L. McCall, T.N.C Venkatesan, A. Passner, A. C. Gossard, and W. Wiegmann, "Optical bistability in a GaAs etalon," in *Proc. Int. Conf. Workshop Opt. Bistability*. New York: Plenum, to be published.

David A.B. Miller, for a photograph and biography, see this issue, p. 311.

S. Des Smith was born in Bristol, England, on March 3, 1931. He received the B.Sc. degree in physics from the University of Bristol in 1952, the Ph.D. degree from the University of Reading in 1956, and the D.Sc. degree from the University of Bristol in 1966.

After research in double half-wave interference filters at Reading, he worked on the optical properties of semiconductors at the Royal Aircraft Establishment in Fanrborough from 1956 to 1958. In 1959 he started research in meteorology at Imperial College, London, and from 1960 to 1970 at Reading University he was responsible for infrared meteorology experiments on the Nimbus 4 and 5 satellites, as well as continuing solid state physics research in lattice dynamics and semiconductor optical properties. He has been Professor and Head of the Department of Physics at Heriot-Watt University, Edinburgh, Scotland, and Chairman of Edinburgh Instruments Ltd. since 1970, and has continued research in semiconductors and quantum electronics.

Prof. Smith was Chairman of the Quantum Electronics Division of the European Physical Society, of which he is a member, for 1977–1980, and is a Fellow of the Royal Society of Edinburgh, the Institute of Physics, and the Royal Society.



Colin T. Seaton was born in Galashiels, Scotland, on April 15, 1957. He received the B.Sc. degree in applied physics from Heriot-Watt University, Edinburgh, in 1979, where he is currently working towards the Ph.D. degree. His research interests include optoelectronic and optical switching and amplifying devices.