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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This project included basic studies of infrared nonlinear optical response and optical switching in semiconductor materials. Investigations ranged from the mid-infrared (InAs) through the 1.06 μm region (InP-based quaternaries) to the near-IR (GaAs/GaAlAs Multiple Quantum Wells). Mechanisms of dynamic state filling were explored; the study was extended to exciton resonance nonlinearities and finally the concept of enhanced carrier transport nonlinearities was introduced. This new non-local nonlinearity is due to the motion of optically induced charges within semiconductor depletion regions causing space charge fields which decrease built-in fields. The optically induced change in internal fields causes nonlinear transmission due to electro-absorption, electro-refraction, and the quantum confined Stark effect. The result was the experimental demonstration of larger nonlinearities than have ever been previously measured, with a change of refractive index of 0.01 at an intensity level of 700 $\mu\text{W}/\text{cm}^2$. (Continued on back)			
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19. ABSTRACT

The most important result of this study was the understanding and development of fundamental new concepts in the nonlinear optical properties of semiconductors, leading to larger nonlinearities at lower power levels than previously known. These concepts can be extended to any direct band materials throughout the infrared region (and even the visible).

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INFRARED ALL-OPTICAL IMAGE PROCESSING IN SEMICONDUCTORS USING THE NONLINEAR INDEX DUE TO DYNAMIC STATE-FILLING

A. STATEMENT OF PROBLEM STUDIED

This program was to investigate semiconductor optical nonlinearities in the infrared portion of the spectrum. The purpose of this study was to explore materials and devices which could act as optical limiters and optical switches.

In this study "infrared" was defined from 0.83 μm to 3 μm . Optical nonlinearities throughout this wavelength region were investigated, in InAs, InP and GaAs-based compounds. Mechanisms of dynamic state filling were explored. The study was extended to exciton resonance nonlinearities in Multiple Quantum Wells (MQW). Finally the effective nonlinearity due to optically induced carrier transport was explored.

B. SUMMARY OF MOST IMPORTANT RESULTS

This project provided results on near-bandgap infrared nonlinear optical response in a variety of semiconductor materials. Nonlinearities due to dynamic band filling in InAs at 3.39 μm were measured. Comparison was made of dynamic band filling with exciton nonlinearities in GaAs/GaAlAs MQW at 0.85 μm . Optically induced changes in internal fields within semiconductor depletion regions were shown to result in large nonlinear absorption and refractive index changes. These were measured in GaAs-based n-i-p-i structures as well as in In-based single hetero-Schottky barriers. Finally, optical computing applications of semiconductor nonlinearities were explored, especially through two-wave mixing in photorefractive GaAs.

Investigations of InAs at 3 μm were motivated by the previous observation of optical bistability at liquid nitrogen temperatures with an HF laser. Our first investigations under ARO sponsorship were to measure InAs nonlinearities closer to room temperature using a 3.39 μm HeNe laser. The result of this analysis was that Auger recombination limits the size of the nonlinearity at warmer temperatures. As a result, large nonlinear response and bistability do not occur due to dynamic band filling in InAs operating close to room temperature.

We continued our research with wider bandwidth materials. In GaAs, MQW show the most promise for large optical nonlinearities, primarily because the MQW exciton has a nonlinearity with a much lower saturation intensity than dynamic state filling. We measured

dynamic state filling and compared it to the exciton nonlinearity in GaAs/GaAlAs MQW materials. Our results confirmed previous reports that exciton absorption saturates at intensity levels an order of magnitude smaller than band-to-band absorption. A careful experimental project to characterize the nonlinearity vs. well size was carried out, using an argon-pumped Styrl 9 dye laser. The result was that both nonlinearities are relatively independent of well size and depend primarily on carrier lifetime. Because the exciton nonlinearity rides on the dynamic band filling nonlinearity, however, these GaAs/GaAlAs MQW have relatively high thresholds for optical bistability ($\sim \text{kW/cm}^2$).

We therefore concentrated our studies on the search for lower threshold optical nonlinearities, introducing the concept of carrier transport nonlinearities. This idea was first explored in n-i-p-i structures. Nonlinearities were seen at intensities of less than a W/cm^2 , but the effects were very small ($\Delta n \sim 10^{-3}$). We therefore developed the new idea of combining heterostructures and n-i-p-i's in the same structure, leading to the multiple-quantum well hetero n-i-p-i (MQW h-nipi). In this material we demonstrated large optical nonlinearities at lower intensities, $\Delta n \sim 0.01$ at $700 \mu\text{W/cm}^2$, giving an effective nonlinearity more than 10^5 times larger than in multiple quantum wells and a thousand times larger than in n-i-p-i structures.

The enhancement of the carrier transport nonlinearity in semiconductor depletion regions was explored in a GaInAsPInP hetero-Schottky barrier designed to operate at $1.06 \mu\text{m}$. We demonstrated a factor of two decrease in absorption at a power level of only 2 mW (0.2 mW/cm^2). The purpose of this research was to demonstrate that the concepts of enhanced carrier transport nonlinearities have general applicability to any direct-band heterojunction material, even those fabricated by liquid phase epitaxy (LPE). Therefore this nonlinearity may be used throughout the infrared and visible portion of the spectrum, using III-V's or II-VI's.

The use of semiconductor nonlinearities for optical computer-related applications was explored, with emphasis on photo-refractive two-wave mixing. In this investigation we demonstrated the use of the polarization properties in photorefractive GaAs to provide high contrast optical switching (5/1) for optical logic elements.

More specific results of these studies are listed here by topic.

1. Optical nonlinearities at the bandgap of InAs

The investigations of InAs at $3 \mu\text{m}$ were motivated by the previous observation of optical bistability at liquid nitrogen

temperatures with an HF laser [1]. Optical bistability at the bandgap in InAs was reported as a hysteresis in the reflected signal from a Fabry-Perot etalon consisting of polished n-type InAs with silver deposited on the back surface. By using the 3.096 μm line of an HF laser, which matches the bandgap at 77 $^{\circ}\text{K}$, bistable switching was achieved with power levels as low as 3 mW (peak intensity 75 W/cm^2). [1]

A detailed study of bandgap resonant optical nonlinearities in n-type InAs and their use in an optical bistable device was carried out by exploring both nonlinear absorption and nonlinear refraction. Good agreement was obtained between experiment and theory using a band-filling model in which the contribution from the light-hole band and the effects of large initial free carrier densities were included. Evidence of the saturation of the nonlinear refraction through the carrier-density-dependent recombination rate was found, and this effect, together with diffraction effects, accounted for the critical power for bistability observed in the reflected signal for an InAs etalon at 77 $^{\circ}\text{K}$ [2].

The large nonlinearity in InAs will be of practical interest only when operation can be achieved closer to room temperature. For these reasons optical nonlinearities were measured with a HeNe laser operating at 3.39 μm in InAs cooled to temperatures of 200 $^{\circ}\text{K}$. Nonlinear changes in transmission at power levels of less than 1 mW were observed. Analysis of these results was made using band-filling for the optical nonlinearities. The experimental results were explained only by including Auger recombination as a dominant lifetime-limiting effect. First principles modelling under these hypotheses gave reasonable agreement between experiment and theory [3].

Because of the saturation of the optical nonlinearity due to Auger recombination, the ability to see optical bistability is reduced [4] and nonlinear switching was not observed. The full understanding of the ramifications of Auger recombination on infrared optical nonlinearities remains to be explored. Because the theoretical analysis of Auger recombination is complex, experimental measurements of carrier lifetime must be made to fully characterize infrared nonlinearities near 3 μm .

2. Dynamic State filling and Exciton-related Nonlinearities in GaAs/GaAlAs Multiple Quantum Wells

Because the dynamic state filling nonlinearity becomes smaller as the wavelength shortens, the threshold for switching and nonlinear response in the near-infrared becomes unsuitably high. We therefore searched for more sensitive nonlinear mechanisms. One example is the exciton-related nonlinearities which occur in



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GaAs/GaAlAs MQW. We explored these and compared them to dynamic state filling.

First we participated, along with P. D. Dapkus from USC, in a study of the growth conditions for achieving the sharp exciton resonances and low intensity saturation of these resonances in AlGaAs-GaAs MQW structures grown by metalorganic chemical vapor deposition (MOCVD). Low growth temperature was found to be necessary to observe this sharp resonance feature at room temperature. The optimal growth conditions were a tradeoff between the high temperatures required for high quality AlGaAs and low temperatures required for high-purity GaAs. A strong optical saturation of the excitonic absorption was observed, along with a saturation intensity of 250 W/cm^2 [5].

The contributions to optical nonlinear absorption in GaAs/AlGaAs MQW structures grown by MOCVD with five different well widths were examined. Excitonic and dynamic state filling nonlinearities were separated and each contribution showed a Bloch-like intensity dependence. To characterize this saturation behavior the effective absorption coefficient and the effective saturation intensity were measured in each case.

The variation with well thickness was compared using the radius of exciton cross section, exciton saturation carrier density, and saturation energy fluence. The results indicated how well the excitons were confined in the quantum well and were explored to determine the optimum nonlinearity. It was found that the saturation intensity is inversely proportional to carrier lifetime, which was largest in the largest wells. However, in these wells the size of the exciton nonlinearity decreased due to decreased exciton confinement. Thus the optimum nonlinearity for optical switching appeared to be about $100 \text{ \AA}$ wells [6].

3. Enhanced Carrier Transport Nonlinearities

Through an understanding of photorefractive effect (discussed below) we came to realize that large effective nonlinearities could be introduced through carrier transport, as used in the photorefractivity, but by enhancing the effect using internally created fields within semiconductor depletion regions. The basic principle is that the internal electric field can be reduced by transport of optically-induced free carriers. These move within the internal fields such as to create a space charge which cancels the built-in field. At high light levels, the internal fields may be removed by the incident light. The change in internal field creates a change in absorption and refractive index through electro-absorption, electro-refraction and, in MQW's, the quantum-confined stark effect. The carrier transport-induced electro-optic effect is

related to the photo-refractive effect, which relies on optical grating-induced electric fields and the non-resonant electro-optic effect. In the ARO program we measured electro-absorption and calculated electro-refraction in a variety of depletion region media.

Our first measurements were of electro-absorption in depletion regions created within the well-known n-i-p-i structures, obtained by alternating p and n regions of a semiconductor, here GaAs. We investigated both pure n-i-p-i structures with 400 Å n and p layers, and hetero-nipi structures, which incorporated transparent GaAlAs p regions along with 2000 Å absorbing GaAs n regions. We found that the nonlinear absorption in the hetero-nipi structure could be explained by the Franz-Keldysh model of electro-absorption [7]. The optically-induced index change was proportional to well width, so the nipi structure showed a larger Δn than the hetero-nipi; $\Delta n = 0.005$ with a saturation intensity₂ (intensity at which Δn changes to half its final value) of 0.2 W/cm^2 .

Our approach was to increase the induced index change by sandwiching GaAs MQW within the i regions of a transparent GaAlAs n-i-p-i structure. The electric-field induced optical changes we measured were therefore due to the quantum confined Stark effect of the exciton resonances within the MQW, rather than the electro-absorption of bulk GaAs. We measured light-induced changes in the absorption at room temperature, using a pump-probe method. Changes in the absorption coefficient in the quantum wells of 1000 cm^{-1} were observed with pump intensities as small as 0.7 mW/cm^2 . Saturation of the nonlinear absorption occurred at 50 mW/cm^2 , with a total absorption change of over 2000 cm^{-1} . Corresponding changes in the index of refraction of ~ 0.02 were calculated [8].

The concept of the enhanced carrier transport nonlinearity offers an important solution for low threshold nonlinear response throughout the infrared and visible regions, since the techniques can be applied to any structure in which pn junctions can be made. This is one of a class of "non-local" nonlinearities, in which, under appropriate conditions, optical bistability can be expected [9].

4. The Depletion Region Electric-field Absorption Modulator

This device, the DREAM, uses an optically induced decrease in absorption near the bandgap energy in a single heterostructure Schottky barrier depletion. A single n-type GaInAsP layer $0.3 \text{ } \mu\text{m}$ thick with a bandgap near $1.06 \text{ } \mu\text{m}$ was fabricated by LPE on a transparent InP substrate. A gold Schottky barrier provided a depletion region devoid of carriers prior to illumination. Upon illumination, electrons and holes created through photoabsorption

are spatially separated by the internal depletion region field. Their accumulation causes a decrease in the voltage across the region as if to forward bias the device. This in turn decreases the electric field and width of the depletion region, which then decreases the absorption via dynamic band filling, electro-absorption and decreased absorption width.

Measurements demonstrated a 50% change in absorption at incident intensity levels of 200 mW/cm^2 , using 1 usec pulses [10]. A numerical model was developed based on a charging capacitor concept which explained the experimental results and indicated that within the depletion region the carrier lifetime is about 500 nsec. We predict larger changes in absorption with a p-n-Schottky barrier; up to a 100/1 contrast ratio should be achieved. Alternative guided-wave geometries are also possible.

The result of this study is that simple LPE fabrication techniques are sufficient to achieve large nonlinearities and low power levels. Thus we expect long-wavelength materials such as InAs, GaSb and related compounds to be applicable to enhanced carrier transport nonlinearities. Furthermore, since carrier densities within depletion regions are negligible, even at room temperature, we expect Auger recombination will not inhibit this carrier transport nonlinearity.

5. Optical Computing applications of semiconductor nonlinearities

Using the photorefractive effect, the carrier transport nonlinearity produces two-wave mixing, a technique of importance for optical computing and optical signal processing. For example, in the proper configuration, AND, OR and NOR have been demonstrated [11]. Two beam coupling in GaAs has been typically very small (typically $\sim 10^{-2}$). Our contribution was to demonstrate a configuration in which the internally generated space-charge field along the $\langle 110 \rangle$ crystallographic orientation causes a rotation in the polarization of the refracted beam. This rotation is the result of simultaneous constructive and destructive coupling for the optical field components along the two electro-optically induced principle dielectric axes of the crystal. Two wave mixing with modulation as much as 500% was observed by turning one of the beams on and off and observing the intensity of the other beam after the crystal and a polarization analyzer [12].

One of the applications for semiconductor nonlinearities is optical switches, which are often envisaged as Nonlinear Fabry-Perot etalons. As part of our studies, we investigated modelling for the materials studied in this program used within an etalon, with emphasis on optical computing applications. Such studies included consideration of an array of pixels imaged through a simple lens to

the etalon. We calculated the limit to the number of parallel elements due to the inclination of the incident beam [13]. This is important since excessive inclination will raise the threshold for optical bistability, when the incident beam has a finite size. The maximum number of pixels in the etalon accessible with a single focussing lens was determined.

The threshold for bistability in the presence of a saturating, lossy nonlinearity was calculated. It was shown that there is a fundamental limitation to the ability of a given material to achieve bistability, based on the ratio of the change in refractive index to the absorption per unit length. We also showed that in many cases, a nonlinear Bragg reflector may be preferable to the Fabry-Perot etalon [14].

Several prospective geometries for integrated optics in optical computing were investigated. These included 2-D, 1-D arrays, single element and integrated opto-electronic devices. Design calculations were presented for optical waveguide addressing of nonlinear etalons, for waveguiding large optical cavity multiple quantum wells and waveguiding nonlinear switches [15].

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C. PARTICIPATING SCIENTIFIC PERSONNEL

Principal Investigator: Elsa Garmire

Alan Kost, Research Scientist

P. S. Jung, Engineers degree, awarded 1986

Paper: "Optical Limitations to Parallel Processing in a Fabry-Perot Etalon"

Th. Papaioannou, MS degree, awarded 1986

Thesis: "Optical Nonlinearities at the Bandgap of InAs at 3.39 μm "

M. Kawase, MS degree, awarded 1987

Thesis: "Excitonic Optical Nonlinear Absorption in GaAs/AlGaAs Multiple Quantum Well Structures"

N. Jokerst, PhD degree, to be awarded 1988

Paper: "The Depletion Region Electric-field Absorption Modulator"

A. Partovi, PhD student

Collaborating Personnel paid from other funds

D. Tsou, PhD student, collaboration in Liquid Phase Epitaxial preparation of samples

Professor P. D. Dapkus and his students, collaboration in MOCVD preparation of samples