Femtosecond Excitonic Optoelectronics

WAYNE H. KNOX, JILL E. HENRY, KEITH W. GOOSSEN, MEMBER, IEEE, KATHRYN D. LI, BENJAMIN TELL, DAVID A. B. MILLER, MEMBER, IEEE, D. S. CHEMLA, MEMBER, IEEE, A. C. GOSSARD, J. ENGLISH, AND S. SCHMITT-RINK

(Invited Paper)

Abstract—We use the sensitivity of the quantum well exciton to applied electric fields to measure electrical transients with femtosecond time resolution. We discuss several mechanisms for femtosecond electrical pulse generation including exciton ionization and two-photon absorption, and we discuss the propagation properties of coplanar striplines on ultrathin semiconductor substrates in the 1–100 THz frequency range. We demonstrate the generation and detection of an electrical pulse with 180 fs risetime propagating on a coplanar stripline on GaAs/AlGaAs quantum wells.

I. Introduction

Excitons [1] in semiconductors represent the fundamental (lowest lying) excitations and result from the Coulomb interaction between the electron and hole. Excitons are sensitive probes of crystal quality and applied fields, and are usually observed at low temperatures in highly pure materials. The recent discovery that excitons in GaAs quantum wells are stable at room temperature [2] has resulted in a flurry of activity in study of the nonlinear optical properties [3], electroabsorption properties [4], and magnetooptical effects [5]. A number of studies of the nonlinear optical response of quantum well excitons in the femtosecond regime have been reported [6]. In addition, fast optical logic gates based on ac Stark effects have been discussed [7]. Thus, our understanding of the basic physics of the excitonic response to perturbations has been steadily improving. In parallel, the field of ultrafast optoelectronics has been developing rapidly. Initial work was based on Auston sampling gates [8], wherein a small amount of charge is shunted out of the circuit to be tested with a photoconducting material that has a fast recombination time. More recently, sampling measurements based on the Pockels effect in $LiIO_3$ or $LiTaO_3$ [9] have been pushed to a time resolution of 280 fs [10] with the external "finger-probing" technique. This represents an important advance in essentially noninvasive testing of ultrafast electrical circuits since the dielectric discontinuities which are introduced by the sampling crystal have been shown to be minor [10]. Sampling based on the electrooptic response of GaAs substrates has been demonstrated [11], as also has sampling relying on internal space-charge fields [12]. In addition, sampling in the gate region of a single-quantum well MODFET has been reported in CW [13] and picosecond time domains [14].

In this paper, we discuss a new approach to the measurement of electrical signals with femtosecond time resolution. We use the parallel-field excitonic electroabsorption effect in GaAs multiple quantum wells [4] to sample the signal which propagates in a coplanar stripline on a very thin substrate (a few microns). Substrate removal is necessary in the GaAs/AlGaAs epitaxy system in order to probe the optical absorption of the quantum-confined exciton layers. This results in new high-speed structures which have unique properties. We also use the quantum wells to generate terahertz electrical transients by several mechanisms: exciton ionization by dc fields [4] and phonons [6a], two-photon absorption [15], and we discuss the possibility of screening by virtual excitons [16], [17]. We finally discuss the unique propagation properties of these novel ultrathin structures.

II. Experiments

Excitonic resonances in semiconductor quantum wells (QW) remain well resolved, even at room temperature [2] and they are strongly modified by application of static electric fields [4]. Two field configurations are possible. For applied fields of 10^3 V/cm–10^4 V/cm parallel to the plane of the layer, the resonances are broadened by field ionization. For fields perpendicular to the layers, the large band edge discontinuities restrict the separation of the electron and hole, resulting in the quantum-confined Stark effect (QCSE) [4] which is characterized by large Stark shifts with well-resolved exciton peaks. QCSE is obtained with fields in the range $\approx 10^5$ V/cm. In both cases, changes in absorption coefficient on the order of $\Delta\alpha \approx 10^3$ cm^{-1} are easily achieved. In the case of GaAs/AlGaAs QW's grown on GaAs, the substrate is opaque at the wavelength where the QW electroabsorption is important and it is necessary to remove it. Several techniques have been developed to remove GaAs substrates, including selective etching for opening mm^2 windows [18] and even total removal of substrate over cm^2 areas [19]. Free-standing films as thin as 0.1 μm can thus be fabricated that exhibit very attractive features for ultrahigh-speed optoelectronics. The structure that we have used in the present experiments is shown in Fig. 1. It con-

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W. H. Knox, J. E. Henry, K. W. Goossen, B. Tell, D. A. B. Miller, and D. S. Chemla are with AT&T Bell Laboratories, Holmdel, NJ 07733.
K. D. Li was with AT&T Bell Laboratories, Holmdel, NJ 07974. She is now with the Applied Physics Department, Stanford University, Stanford, CA 94305.
A. C. Gossard and J. English were with AT&T Bell Laboratories, Murray Hill, NJ 07974. They are now with the Department of Materials, University of California, Santa Barbara, CA.
S. Schmitt-Rink is with AT&T Bell Laboratories, Murray Hill, NJ 07974.
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sists of a free-standing QW film with thin gold coplanar striplines evaporated onto the film. We shall discuss in detail the high-frequency properties of this structure later. For the moment, a qualitative analysis will suffice to show its unique potential for ultrafast optoelectronics. As shown in the inset of Fig. 1, when a voltage is applied to the conductors, the field lines on the top are in air, and at the bottom, the fields lines are mostly in air as well. Relatively few field lines remain in the dielectric. This structure therefore has a low effective dielectric constant, resulting in a high propagation speed and very low dispersion and radiative losses. Furthermore, the high-quality semiconductor film itself can be used for generating electrical transients by using ultrashort optical pulses to produce real [8] or virtual [16], [17] shunts between the lines. These electrical transients, as they propagate along the lines, produce a transient electroabsorption in the QW film that can be used to optically probe the field within the QW. The device shown in Fig. 1 provides simultaneously the means to *generate*, *propagate*, and *detect* electrical transients with terahertz bandwidth.

The sample we have used for these experiments consists of a 0.708 μm GaAs/AlGaAs multiple QW layer and a 1.97 μm thick stop-etch layer of $Al_{0.32}Ga_{0.68}As$ grown on a semi-insulating GaAs substrate. The multiple-QW layer comprises 50 periods of 69.3 Å $Al_{0.32}Ga_{0.68}As$ barrier layers and 72.25 Å QW's. The QW's themselves consist of a five-period superlattice: 11.5 Å GaAs layers and 2.95 Å $Al_{0.32}Ga_{0.68}As$ layers. This unusual composition [20] adjusts the exciton energy to near resonance with our femtosecond laser source. The wafer is proton-implanted, with the energy and dose of the implant carefully chosen to create semi-insulating quantum wells, yet avoiding significant defect broadening of the exciton resonances, and the carrier lifetime is then reduced to about 50 ps [21]. A 10 μm gold coplanar stripline is patterned onto the top (QW) side of the wafer, and the back region is then carefully removed over a 1 × 1.3 mm area by a selective etch solution which stops the at the $Al_{0.32}Ga_{0.68}As$ layer. Thus, we obtain a free-standing film of ≈ 2.7 μm thickness with the 10 μm gold coplanar stripline attached.

We apply a dc bias to the electrodes, and thus obtain a parallel-field excitonic electroabsorption in the region between the electrodes. We first characterize the modulation of light which is obtained when a dc voltage is applied to the stripline structure. Fig. 2 shows the relative transmission change which is obtained when applying a 5 V modulation around a 10 V dc bias and 40 V bias. When the electric field is applied in the plane of the layers, the excitons are field ionized. The shortening of the exciton lifetime results in a strong broadening of the resonance. For high fields ($> 10^4$ V · cm^{-1}), the resonance width increases approximately linearly with the bias field. Consequently, the frequency width of the modulation region increases as the dc bias is increased. The width of the exciton line is a direct indicator of the local electric field inside the quantum wells, and it provides essentially an "instantaneous" measure of the applied field. Fig. 3 shows the peak transmission change as a function of voltage, demonstrating that at low fields, the modulation is quadratic, whereas at high fields, it becomes quite linear. The slope is about 1 percent/V applied; thus, the QW exciton is a sensitive detector of applied fields. At higher voltages, the modulation begins to saturate, and then electrical breakdown occurs. For comparison, we note that a Pockels modulator with a 2 kV half-wave voltage has a

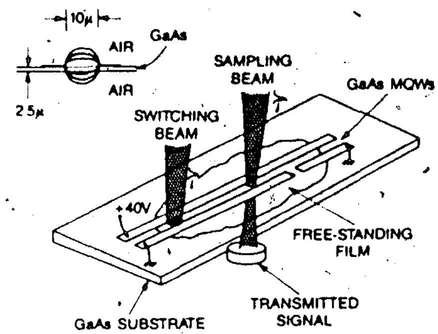

Fig. 1. Sample structure. A 10 μm gold coplanar stripline which is 5 mm long is patterned onto a sample composed of 0.7 μm of GaAs quantum wells on top of 1.97 μm of stop etch AlGaAs layer. The substrate is removed in a 1 × 1.3 mm area. A pump beam excites the stripline and the probe beam samples the excitonic electroabsorption response anywhere in the circuit. The inset indicates that the field lines propagate in air on both sides of the dielectric.

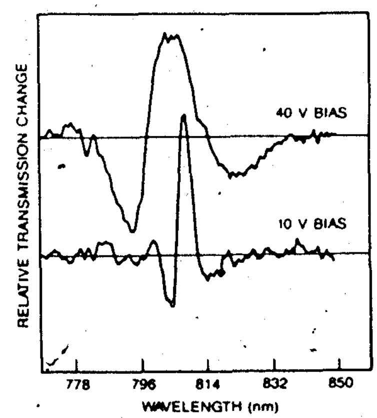

Fig. 2. Differential spectrum measured with light bulb in between contacts. A 5 V signal is chopped at low bias (10 V) and high bias (40 V) and the resulting differential transmission signal is measured. At high fields, the line is broadened by field ionization in less than 100 fs.

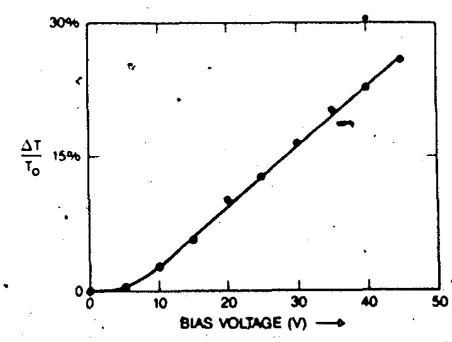

Fig. 3. Linearity of detection. The peak transmission change as a function of voltage shows a reasonably linear response over a range of 30 V. At low voltages, the signal varies quadratically with bias. The modulation sensitivity is about 1 percent/V in a 10 μm line.

sensitivity of about 0.1 percent/V. We have not attempted to optimize the 1 percent/V excitonic detection sensitivity, and it is likely that higher values could be obtained in smaller structures or with different quantum well parameters.

For the transient-field experiments, a pump beam that consists of a train of ultrashort optical pulses is focused to a ≈ 15 μm diameter spot on the sample, either across the stripline in the so-called "sliding-contact" excitation mode or in the gap region (Fig. 1). The photocarriers generated by the pump produce a transient change of the QW-dielectric constant between the conductors, sending an electrical transient propagating down the line. A weak probe beam is incident between the two gold conductors at the position to be sampled. To detect the electrical signal as a perturbation of the bias voltage, the variation of the probe intensity transmitted through the QW sample is measured. We use a two-jet synchronously pumped dye laser which produces pulses of 100–150 fs duration at $\lambda = 805$ nm [22]. This laser cannot be tuned since it operates in a strong passive mode-locking condition. Two different types of experiments are performed. First, we use the unamplified femtosecond pulses at high repetition rate (82 MHz) obtained directly from the laser with a fixed wavelength. In the second set of experiments, the 805 nm pulses from the laser are amplified at 8 kHz repetition rate and converted to white light continuum pulses [22]. We then use an interference filter to select the desired the excitation wavelength.

A. Resonant Excitation

In the first experiment, the pump and probe are directly derived from the laser at an 82 MHz repetition rate. The average power in the pump beam is a few mW and the probe is ≈ 100 times weaker. The pump beam is passed through a chopper at a 1 kHz rate and a variable delay is introduced between the pump and the probe by a 100 nm resolution stepper motor. The transmitted probe beam is collected by a photodiode, detected by a lock-in amplifier, and digitized with a computer. The high repetition rate allows extensive signal averaging; however, the wavelengths of the pump and the probe are identical and nontunable. The special design of the QW composition described above tunes the excitonic absorption close to the laser wavelength (pure GaAs QW of this thickness would have excitons at ≈ 840 nm). The sample is mounted into a thermoelectrically controlled copper block which can be operated between +40 and −35°C to fine tune the exciton absorption to the laser wavelength. In these experiments, the excitation of the stripline is at the center of the exciton resonance, so that initially excitons and no free carriers are created in between the stripline. At room temperature and in the absence of dc field, these excitons are ionized in a time ≈ 300 fs by collision with LO phonons, thus releasing free electron–hole pairs with substantial excess energy [6a]. In the presence of large dc fields, however, the excitons are not in bound states. The wave functions correspond to electrons and holes which, although still correlated, are separated by average distances large as compared to the Bohr radius. These states correspond to the open hyperbolic orbits of classical mechanics, as opposed to closed elliptical orbits of the bound states. Using the inverse of the resonance linewidth as a measure of the times it takes the electron and hole to tunnel away one from another, we estimate that photocarriers are released in less than 50 fs, at the fields typically used in our experiments. Fig. 4 shows the signals which are obtained under these conditions with the pump and probe beams separated by about 150 μm. In Fig. 4(a), the initial transient is shown. We obtain risetimes of 500–700 fs for this condition, even when the laser pulses are 100–150 fs in duration. The initial rise is followed by a reproducible decay. Fig. 4(b) shows the signal under similar conditions, but on a longer time scale, illustrating the formation of reflections at later times which occur as a result of the gap region and the dielectric interfaces at the edges of the sample. The fastest risetimes obtained in this mode are 500–700 fs, apparently not limited by the laser pulse duration. The time resolution of this experiment could, in principle, be limited in the generation stage, the propagation stage, or the detection stage. We have previously shown that the excitonic time response to a rapidly changing electric field is at least as fast as 330 fs [23], although this experiment did not allow for propagation studies over macroscopic distances. The dispersion of the present structure is not strong enough to explain this result, as we discuss in the next section. This suggests that the risetime could be limited by the excitation process. In this case, we excite exactly at the absorption edge, which generates carriers with zero excess energy. The transient photoconductivity of a cold plasma in a warm lattice with electric field applied does not appear to have been studied before; usually, experiments are done with excitation far above the band edge, which creates high excess energy carriers initially. We measure a propagation speed of about 1.4 times slower than the speed of light for this structure.

Although the excitonic electroabsorption is a sensitive detector of applied fields, its use as a sampling detector is limited by several new problems. First, the ultimate detection sensitivity is limited (at the shot-noise limit) by the probe beam intensity. In the case of electrooptic detector materials, probe beam powers of several mW can be used; however, in the case of excitonic electroabsorption detection, lower powers are necessary to avoid self-saturation of the probe [2], [3] and excessive probe-induced photocurrent. Of course, no sampling technique is truly noninvasive, and in the case of excitonic electroabsorption, the probe beam photocurrent is the perturbation to the circuit. Interestingly, electrooptic sampling also in principle causes a transient to be generated by the probe beam by optical rectification [24]. For the quantum well sampling technique, this point needs more investigation. A further problem is that in the present experiment, we use a synchronously pumped two-jet femtosecond laser to provide light pulses in resonance with the exciton [22]. It

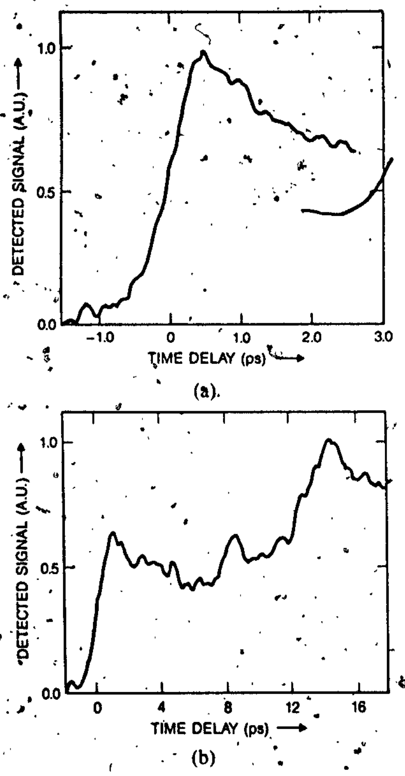

Fig. 4. Signals detected with resonant excitation at 82 MHz. (a) Signal with 150 μm pump-probe pacing on fast time scale. Risetimes of 500–800 fs are obtained in this condition. (b) Same conditions, but on longer time scale showing reflection at gap and dielectric discontinuities at GaAs edges. Initial relaxation is of unknown origin, but could be a velocity overshoot starting from $k = 0$ or a contact relaxation effect.

is well known that these lasers have poor noise performance compared to CW-pumped colliding-pulse mode-locked lasers [25]. The probe beam saturation problem combined with the excessive noise spectrum of the synchronously pumped laser account for the relatively poor signal-to-noise ratio of the data at present as shown in Fig. 4 compared to other sampling techniques. Recently, a Ti–sapphire laser-pumped colliding-pulse mode-locked dye laser operating at 820 nm has been demonstrated [26] which should provide significantly improved noise performance for this application.

Calibration is an important issue in any measurement technique. We estimate that the peak voltage is a few hundred mV from the average photocurrent, repetition rate, and estimated carrier lifetime. If we assume that the modulation sensitivity for femtosecond signals is also about 1 percent/V as in the dc case, we expect signals in the range of one part in 1000 transmission change. This is approximately the peak signal in Fig. 4. Clearly, more work is needed in calibration techniques.

B. Below Resonance Excitation

In the second set of experiments, the 805 nm pulses from the laser are amplified at an 8 kHz repetition rate and converted to white light continuum pulses [22]. In this case, we obtain much higher energy per pulse, but at a lower repetition rate, and using interference filters we can excite below, at, or above the excitons, thus choosing the energy and nature (real or virtual) of the photocarriers. For these experiments, we replace the chopper with a shutter which is synchronized to the scanning of a differential detection optical multichannel analyzer/spectrometer which allows us to record the time-resolved differential transmission spectra at the probe spot [27]. We cool the sample to 250 K, placing the exciton wavelength at about 785 nm, so that the high-intensity continuum pulses occur at energies below the bandgap energy. This is the optimal condition for studying several new excitation mechanisms for femtosecond electrical pulse generation. By pumping below the band edge, we can explore effects which are due to virtual carrier generation, such as ac Stark effect [28], [29] and field-induced optical rectification [16], [17] which has been proposed. We have previously studied the ac Stark effect in dc-biased quantum wells in the perpendicular field geometry [15], but we did not obtain propagating components, due to dielectric dissipation in the dopant layers. In the present case, the use of coplanar striplines provides efficient and well-defined propagation modes, and excitation below the band edge allows us to measure *the exact system excitation response function at the generation point* since the ac Stark effect is essentially instantaneous. In fact, the virtual carriers have an effective lifetime of the inverse detuning, which is only tens of femtoseconds for this experiment. We therefore first measure the ac Stark effect with the pump and probe pulses overlapped in the stripline without applied bias. The frequency-integrated ac Stark signal is shown in Fig. 5(a). This signal has an FWHM of about 170 fs, which results from the pump and probe pulses having durations of about 100 fs. We consider this as the system excitation function at the generation point. The frequency integration of the differential transmission spectra recovers the exciton dynamics free of pump-induced polarization effects [30], and yields the phase-space filling component of the ac Stark effect due to virtual carrier populations. We find that this signal does not return to zero at late times because at high intensities (5–10 GW $\cdot$ cm^{-2}), the subbandgap excitation produces a significant two-photon absorption excitation, which places extremely hot carriers about 1.5 eV above the band edge. The hot carriers, whose energy greatly exceeds the two-dimensional confinement potential (about 250 meV), are free to move in three dimensions and instantaneously screen the exciton absorption [15]. We then move the probe beam about 100 μm away from the pump spot and measure the frequency-integrated probe differential transmission signal. This transient exhibits a risetime of about 180 fs, which is the fastest guided-wave electrical signal which has been reported. It contains two contributions: the step response is due to the two-photon generated real carriers, and the ringing is the first indication of switching from virtual excitons [16], [17]. Other results obtained at lower intensities give further indications of virtual carrier-induced switching with smaller contributions from two-photon absorption. These results will be reported else-

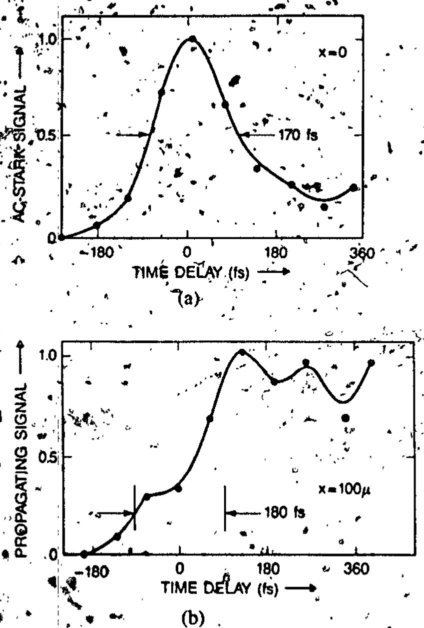

Fig. 5. Signals generated with subbandgap excitation at 815 nm with exciton line at 785 nm. (a) Frequency-integrated ac Stark effect with pump and probe beams overlapped showing an FWHM of 170 fs. This represents the true system response function including pump and probe pulsewidths. The finite tail at late times is from two-photon absorption. Pump intensity is about 5 GW/cm^2. (b) Propagating signal at 100 μm distance. Signal exhibits a 180 fs risetime. The step part of the transient is due to two-photon carrier generation, and the ringing may be due to virtual transient generation.

where. The fast switching transient response indicates that our structure has extremely low dispersion, and that the excitonic response is very fast as well. The excitonic response is expected to be very fast since the width of the exciton line is essentially a probe of the internal electric field at the instant a photon is absorbed. More fundamental arguments can be used to address the issue of the ultimate time response of the exciton; they will be reported elsewhere. Further experiments along these lines are in progress. This result appears to corroborate our claim that the 500–700 fs risetimes obtained in the previously discussed resonant excitation experiments (Fig. 4) are due to creating carriers only at the very bottom of the band. Signal levels of a few percent transmission change are obtained, corresponding to switched signals of a few volts.

III. Propagation Modeling

We consider now the dispersion and loss characteristics of coplanar stripline structures in the ultrathin substrate limit. We have considered two different cases: first, the case of only modal dispersion and conductor and radiation losses, but using a fixed dielectric constant for the substrate, and second, incorporating the phonons via a frequency-dependent dielectric function. Using our approach, the phonons may be incorporated only for very thin substrates.

The voltage (V) on a transmission line at a point z at time t is given by

$$V(z, t) = F^{-1}\left[e^{\gamma z} F[V(0, t)]\right] \tag{1}$$

where F and F^{-1} denote the Fourier transform operator and its inverse, respectively, and $\gamma = -\alpha + i\beta$ is the propagation function of the line. The problem is then reduced to characterization of the transmission line in the frequency domain. We define

$$\beta = \frac{2\pi f}{c} n_{\text{eff}} \tag{2}$$

where f is the frequency of the signal, c is the speed of light, and n_{eff} is the effective refractive index of the line.

Any two-conductor line may support a quasi-TEM mode which has no cutoff frequency. The effective index of the line for this mode is constant for signal wavelengths much longer than the dimensions of the line. In mixed air–dielectric lines like our coplanar stripline, this effective index has a value between the indexes of air and the dielectric, and is determined by the percentage of field lines in either. It essentially can be determined from a static model. As the wavelength becomes comparable to line dimensions, the field distributions of the mode change, so that the effective index changes. Typically, at wavelengths much shorter than line dimensions, all of the field lines are confined in the dielectric, so that the effective index is that of the dielectric ($n = \epsilon_r^{1/2}$). Therefore, the effective index goes through a transition from its static value to that of the dielectric at wavelengths near the line dimensions.

The static effective index $n_{\text{eff}}^{(0)}$ for coplanar striplines whose substrate depth (d) is infinite has been determined by Wen [31]. Conformal mapping is used to map the coplanar geometry into a parallel plate geometry wherein half of the volume is occupied by the dielectric. This results in

$$\left[n_{\text{eff}}^{(0)}\right]^2 = \frac{\epsilon_r + 1}{2} \quad (\infty \text{ substrate}). \tag{3}$$

For GaAs ($\epsilon_r = 13.1$) substrate coplanar striplines, this results in $n_{\text{eff}}^{(0)} = 2.66$. Static analysis for finite d has been performed by Davis *et al.* [32]. The finite thickness of the substrate produces a void in the dielectric when it is mapped into the parallel-plate configuration. Bahl *et al.* have derived the following formula by curve fitting to this analysis [33]:

$$\left[n_{\text{eff}}^{(0)}\right]^2 = \frac{\epsilon_r + 1}{2}\left[\tanh\left(1.785 \log\left(\frac{d}{w}\right) + 1.75\right) + \frac{kw}{d}\left(0.04 - 0.7k + 0.01\left(1 - \frac{\epsilon_r}{10}\right)\left(\frac{1}{4} + k\right)\right)\right]. \tag{4}$$

Here, w is the width of the conductors and $k = s/(s + 2w)$ where s is the spacing between the conductors. However, this formula is invalid for $d/w < 1$, which is the case we are interested in.

Presented here is an analysis of the static effective index for very thin substrates. In this case, when mapped into the parallel-plate geometry, the "void" becomes large so that there is only a thin shell of dielectric between the plates. We find that the mapping can be performed to first order in d to obtain the thickness of the shell; then we obtain an approximate formula for the effective index by using the shunt-series capacitance techniques of Wheeler [34]:

$$[n_{\rm eff}^{(0)}]^2 = 1 + \frac{1}{2b}\left[\epsilon_r d + \frac{q_a a}{a - q_a(1 - 1/\epsilon_r)} + \frac{q_b a}{a - q_b(1 - 1/\epsilon_r)} - (d + q_a + q_b)\right]. \quad (5)$$

Here, $a = K(k)s/2$, $b = K(k')s/2$, $q_a^2 = \zeta(w + s/2)d$, $q_b^2 = \zeta(s/2)d$ where $\zeta = s(s + 2w)/[4w(s + w)]$, $k' = (1 - k^2)^{0.5}$, and K is the complete elliptic integral of the first kind. If $|q_{a,b}(1 - 1/\epsilon_r)| << a$, which is typically true except if ϵ_r approaches zero (e.g., near phonon energies),

$$[n_{\rm eff}^{(0)}]^2 = 1 + \left(\frac{d}{s}\right)\frac{(\epsilon_r - 1)}{K(k')}\left[1 + \frac{1}{(1 - k)K(k)\epsilon_r}\right]. \quad (6)$$

For GaAs substrate $\epsilon_r = 13.1$ coplanar striplines with $w = s = 10$ μm, this becomes to a good approximation $[n_{\rm eff}^{(0)}]^2 = 1 + d/2$ for d in μm. As expected, as the substrate thickness goes to zero, the effective index goes to 1. Therefore, signals will propagate faster on lines whose substrate is thinner than a few microns than on thick substrate lines.

As mentioned, the effective index changes with frequency. Hasnain *et al.* have performed a full-wave analysis of coplanar striplines, and have curve fitted to these results to obtain [35]

$$n_{\rm eff} = n_{\rm eff}^{(0)} + \frac{n - n_{\rm eff}^{(0)}}{1 + aF^{-1.8}}. \quad (7)$$

Here, $F = f/f_{\rm TE}$, $f_{\rm TE} = c/[4d(\epsilon_r - 1)^{0.5}]$ is the cutoff frequency above which the first non-TEM mode may propagate, and $\log(a) = u \log(s/w) + v$ where $u = 0.54 - 0.64q + 0.015q^2$, $v = 0.43 - 0.86q + 0.540q^2$ with $q = \log(s/d)$. From this formula, the maximum dispersion occurs at a frequency $f_{\rm disp} = a^{0.56} f_{\rm TE}$.

The dispersion frequency increases rapidly as the substrate becomes thinner. For $d = 2.5$ μm, (GaAs, $w = s = 10$ μm) $f_{\rm disp} = 9.9$ THz. For $d = 100$ μm, $f_{\rm disp} = 2.3$ THz. Fig. 6 shows the result of propagating a 100 fs risetime pulse on the 2.5 (a) and 100 (b) μm thick substrates. The pulse has some frequency components which extend beyond 10 THz. This produces the ringing present for the 2.5 μm substrate since these high-frequency components propagate more slowly. The propagation speed is $c/1.5$, close to the experimentally measured value of $c/1.4$ considering our level of approximation of the structure with our model. After 150 μm, the risetime of the pulse is 150 fs. For the 100 μm thick substrate, however, the pulse is strongly dispersed. The sharp edge of the pulse consists of frequencies above the dispersion frequency, so that it propagates at c/n(GaAs). The lower frequency components propagate according to the effective static index, so they appear sooner, leading to a long rise time for the pulse.

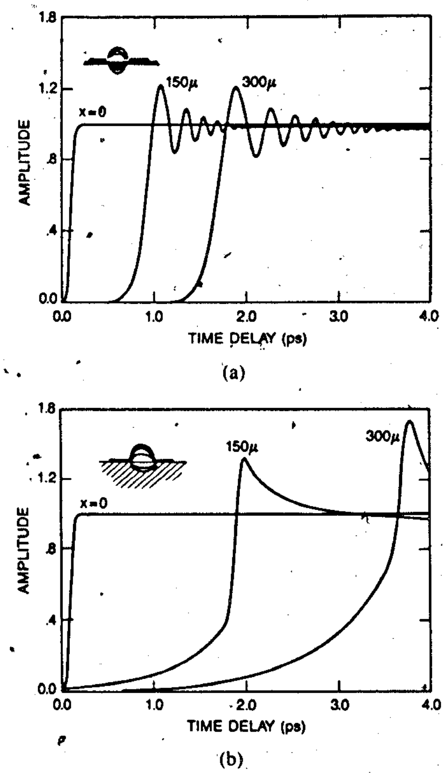

Fig. 6. Model for propagation containing modal dispersion and conductor losses. (a) 2.5 μm substrate thickness with 100 fs risetime step input. (b) Same but with 500 μm thick structure. The advantage of a thin structure is apparent from this analysis.

Fig. 7(a) shows the effective index (7) as a function of frequency for different substrate thicknesses. For very thin substrates, the modal dispersion vanishes. We note that for some band-limited pulse shapes, propagation on thick substrates may be better than on thin substrates (less net pulse distortion upon propagation); however, for the broad-band case, the thin substrate is the only good solution.

Next, we wish to include the effects of phonons since the TO frequency in GaAs is 8 THz, and this should have significant effects on propagation of 100 fs pulses. In order to properly include the effect of a substrate dielectric function which varies with frequency near the geometric dispersion frequency, we would have to perform a full-wave analysis which is extremely complex. In the very thin substrate limit, negligible geometric dispersion is obtained, and material dispersion becomes most important. In this case, any frequency component near the phonon frequency can be considered to be in the static limit. The dispersion frequency is 64 THz for a 0.5 μm substrate

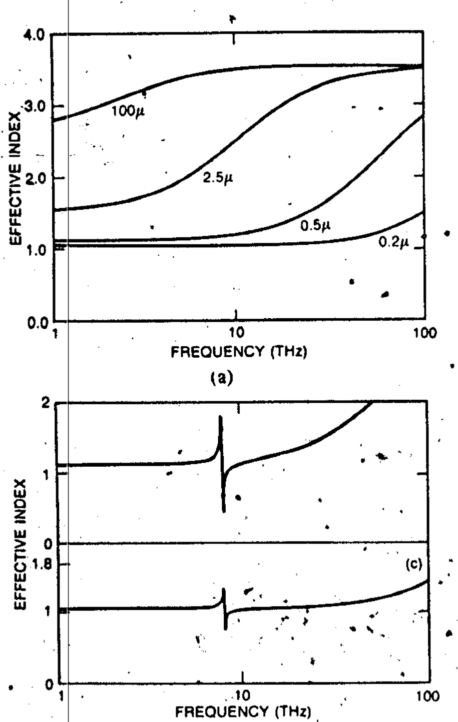

Fig. 7. Frequency dependence of effective index for (a) case of modal dispersion, conductor, and radiation losses only for four thicknesses of substrate, (b) in the thin substrate (static) limit including phonons for 0.5 μm thickness, and (c) same as (b), but 0.2 μm thickness. The phonon contribution goes to zero as the thickness goes to zero because of the geometric filling factor.

(using $\epsilon_r = 10.9$). Then it is correct to substitute the dielectric function of GaAs including phonons [36] for ϵ_r in our expression for the static effective index. Our "static" effective index is now frequency variant. We may still include geometric dispersion at frequencies much greater than the phonon frequency, by using the optical substrate dielectric constant in (7). Note that the static index has an imaginary component due to phonon loss, so that β does also, which leads to an additional loss component in (1). We will show, however, that in the ultrathin substrate limit, not only does the modal dispersion problem vanish, but also the problem of phonon absorption is minimized, and it should be possible to propagate electrical pulses of less than 100 fs risetime over macroscopic distances. Fig. 7(b) shows the effective index (7) with a frequency-dependent dielectric function for the 0.5 and 0.2 μm thick structures. The TO phonon induces a smaller effect in the thinner substrate case due to the geometric filling factor. Fig. 8(a) shows the propagation of an 80 fs risetime electrical pulse in a structure of 0.2 μm thickness, Fig. 8(b) shows the same with a 0.5 μm thickness, and Fig. 8(c) shows the result of propagation in a buried stripline for comparison. Of course, we cannot probe the excitonic electroabsorption if the stripline is buried in GaAs, and burying it in AlGaAs is impractical so this is not a good way to remove the modal dispersion problem. Clearly, the ringing which is due to the interaction with the phonons becomes less severe as the substrate thickness is reduced. Fig. 9 shows the same calculation, but using an

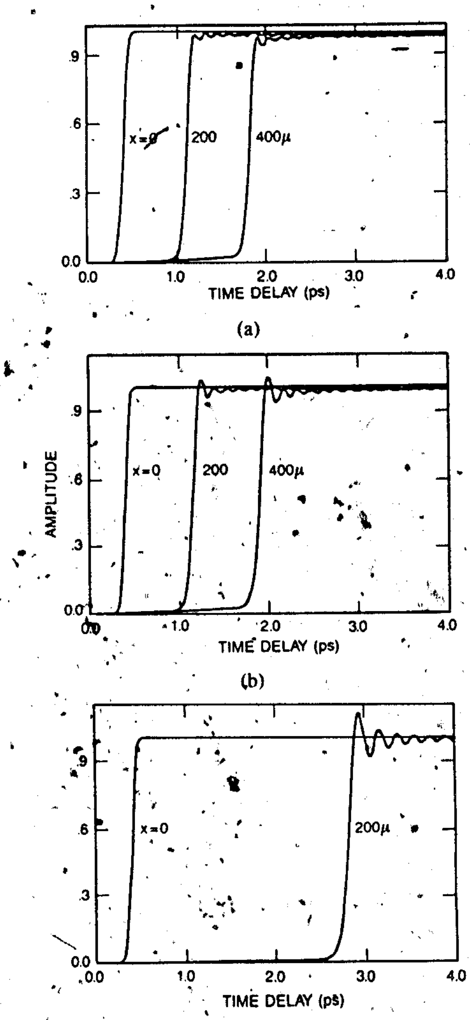

Fig. 8. Model for thin substrate limit containing phonons. (a) 0.2 μm thick sample with 80 fs step input, (b) 0.5 μm structure thickness, and (c) buried stripline in GaAs for comparison. Clearly, thin substrates also reduce coupling to phonons due to filling factor.

80 fs differential pulse as the input. Such a pulse has no low-frequency components, and could be generated by a field-induced optical rectification [16], [17]. Although this mechanism for generation was proposed in [16] and [17], the methods for propagation and detection were not discussed. Fig. 9(a) shows the propagation of the 80 fs derivative transient in a 0.2 μm structure, Fig. 9(b) shows the propagation in a 0.5 μm structure, and Fig. 9(c) shows the propagation in a buried structure. For this case, Fig. 10 shows the corresponding power spectra for the electrical pulses before and after propagating a distance of 400 μm. Clearly, the thin substrate reduces the fundamental problem of phonon interactions. In the buried structure, all frequency components around 8–10 THz are destroyed by the phonons. The other frequencies are not absorbed by this narrow resonance, although the dispersion extends for several THz on either side of the resonance. For the thinner structures, the effect is to impose a weak ringing at the phonon frequency. Therefore, this modeling indicates that these structures can be used for optoelectronics well into the regime of less than 100 fs. We are presently

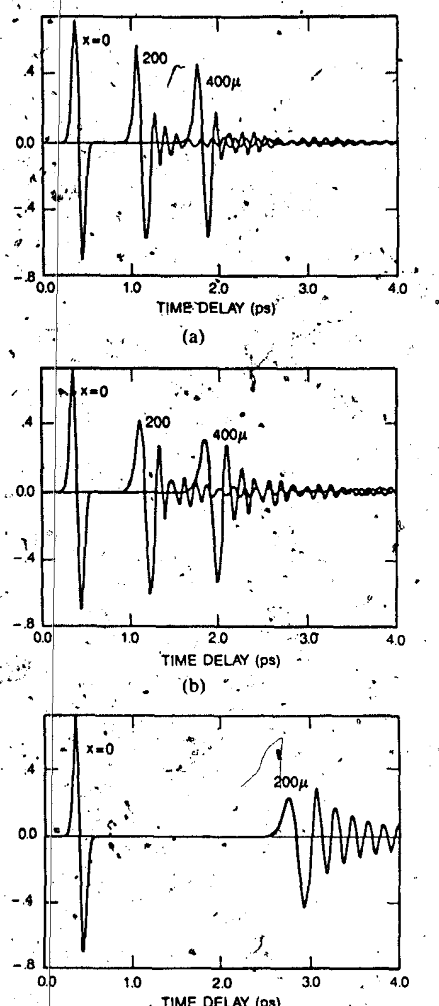

Fig. 9. Same model as in Fig. 7, but with an 80 fs differential pulse input, as would be generated by a virtual displacement current (ac-dc Stark effect). (a) 0.2 μm structure, (b) 0.5 μm structure, and (c) the buried stripline in GaAs for reference.

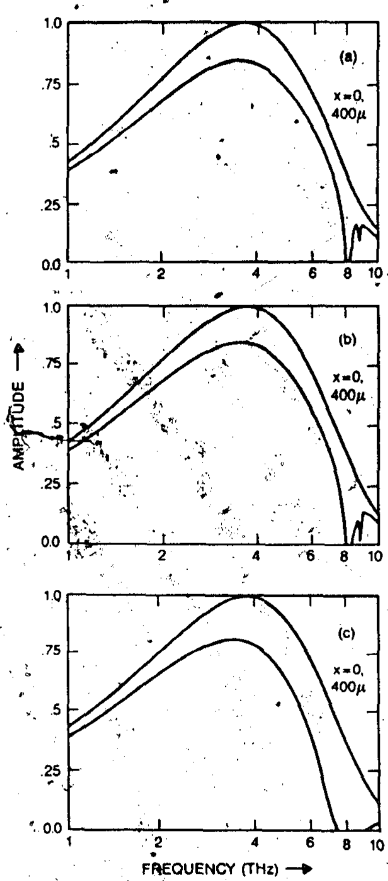

Fig. 10. Power spectra for the case of Fig. 9, showing absorption from the phonons at 8 THz. The buried stripline eliminated modal dispersion; however, the phonon absorption is severe. The overall loss is from conductor losses. (a) 0.2 μm structure, (b) 0.5 μm structure, and (c) buried stripline in GaAs.

fabricating devices with thinner substrates and expect to test these models in the very high-frequency regime. As mentioned previously, for some band-limited pulses, thick substrates can actually provide propagation with less net modal dispersion if all the frequency components propagate above the TE cutoff frequency, however, multimode dispersion should be considered.

We consider our analysis to be preliminary, and recognize that the inclusion of material dispersion and loss via a direct insertion of the dielectric function is approximate. In any case, a full-wave analysis is desirable, and we are investigating this. Further problems involve the inclusion of multiphonon processes for higher frequency components.

IV. Summary

We have discussed a new approach to femtosecond optoelectronics which uses the excitonic response to electric fields as a detector and the excitonic nonlinear response to optical fields as a generator. We have investigated the propagation properties of structures which push into a new regime: ultrathin substrates. As the substrates become thinner, fundamental loss and dispersion limits are extended. In the future, we hope to incorporate ultrafast electronic and optoelectronic devices into these GaAs structures, and develop contactless and reflection-type excitonic electroabsorption probes for other purposes. In addition, devices with electric fields applied perpendicular to the quantum well layers could be used in microstrip or other geometries.

Note Added in Proof: We find that the rise and decay of the signal shown in Fig. 4(a) depend strongly on electric field, suggesting that a field-induced carrier heating causes intervalley transfer (velocity overshoot). This will be published in W. H. Knox and S. M. Goodnick, *Appl. Phys. Lett.*

Also, we recently completed a full-wave analysis including phonons for any substrate thickness. This will be published in G. Hasnain, K. W. Goossen, and W. H. Knox, *Appl. Phys. Lett.*

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Wayne H. Knox was born in Rochester, NY, in 1957. He received the B.S. and Ph.D. degrees from the Institute of Optics, University of Rochester, Rochester, in 1983, performing his research at the Laboratory for Laser Energetics.

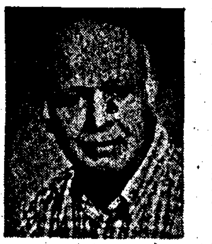
He worked as a postodoctoral member of the Technical Staff at AT&T Bell Laboratories, Holmdel, NJ, from 1984 to 1985 and is now a member of Technical Staff in the Quantum Physics and Electronics Research Department. His research interests include the physics of semiconductors and defects in insulating crystals, nonlinear optics, femtosecond spectroscopic and optoelectronic measurements, and coherence properties of optical fields.

Dr. Knox is a member of the Optical Society of America, the American Physical Society, and the Lute Society of America.

Jill E. Henry for a photograph and biography, see p. 1927 of the August 1989 issue of this JOURNAL.

Keith W. Goossen (M'83-S'87-M'87), for a photograph and biography, see this issue, p. 2607.

Kathryn D. Li, for a photograph and biography, see p. 288 of the March 1989 issue of this JOURNAL.



Benjamin Tell was born in Philadelphia, PA, on December 11, 1936. He received the B.A. degree in physics from Columbia University, New York, in 1958 and the M.S. and Ph.D degrees, also in physics, from the University of Michigan in 1963.

He has been with AT&T Bell Laboratories, Holmdel, NJ, since 1963. He spent one year on an exchange at the Phillips Research Lab, Eindhoven, The Netherlands. He has worked on various ultrasonic, optical, and electrical properties of semiconductors and semiconductor devices. He has most recently been involved with ion implantation on III-V materials and devices. He has coauthored approximately 100 technical papers and several patents.

David A. B. Miller (M'84), for a photograph and biography, see p. 1927 of the August 1989 issue of this JOURNAL.

D. S. Chemla (M'84) was born in Tunis, Tunisia, on July 21, 1940. He graduated from the Ecole National Superieure des Telecommunications, Paris, France, in 1965, and received the Doctorat Es-Sciences from the Faculty of Sciences at Paris in 1972.

From 1965 to 1967 he worked at the College de France in high-energy physics. From 1967 to 1981 he worked at the Centre National de'Etudes des Telecommunications as an MTS Group Leader and Department Head. He joined AT&T Bell Laboratories, Holmdel, NJ, in 1981 and is now head of the Quantum Physics and Electronic Research Department. He has been engaged in research on nonlinear optics of insulators, organic molecules, and crystals and semiconductors. He is currently interested in the optical response of microstructures under excitation by ultrashort and high intensity light pulses.

A. C. Gossard was born in Ottawa, IL. He received the B.A. degree in physics from Harvard University, Cambridge, MA, and the Ph.D. degree in physics from University of California, Berkeley.

Prior to 1987, he was a member of the Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ, where he engaged in research on magnetic resonance properties of magnetic and metallic materials and on molecular beam epitaxy development of semiconductor quantum structures. Since 1987, he has been a Professor of Materials and Electrical and Computer Engineering at the University of California, Santa Barbara, where he is pursuing further research on the growth, properties and applications of quantum microstructures.

Dr. Gossard is a Fellow of the American Physical Society, a member of the National Academy of Engineering, and a recipient of the 1986 Oliver Buckley Condensed Matter Physics Award of the American Physical Society.

J. English, photograph and biography not available at the time of publication.

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