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frequency side of the Fabry–Perot peak. All the other gates can be constructed using NOR gates.

In conclusion, we have demonstrated for the first time an 1-ps operation of an optical NOR gate using a GaAs-AlGaAs nonlinear etalon at room temperature and a femtosecond laser system. These measurements show that an etalon transmission peak can be shifted in 1 ps. The NOR gate contrast is only 2.5 because our probe pulses are shorter than the cavity response time of the etalon, which broadens the Fabry–Perot peaks, giving lower contrast for the same shift. Shorter cavities or longer (still subpicosecond) pulses will alleviate this problem. Recently a similar device exhibited a contrast of more than 6 to 1 at a 82-MHz rate with less than 3 pJ of energy incident on a 5–10-μm diameter.

The measured speed of this gate also suggests that similar MQW or bulk GaAs bistable switches should have the same switch-on times (the fastest measured switch-on time previously reported for a bistable device is detector-limited 200 ps). Even though the gate speed is 1 ps, the next operation cannot be made for a few nanoseconds, because it takes that long for the free carriers to recombine or diffuse out of the illuminated region and allow the index of refraction to return to its initial value. This limits the cycling rate to a few hundred megahertz, but 10^{14} operation per second. Carrier recombination times in GaAs have been significantly reduced by doping, proton bombardment, and surface recombination; such techniques have not been tried for nonlinear etalons.

An array of such devices on the same etalon would allow parallel logic operations and may also be used as an all-optical addressable spatial light modulator.

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**Optical properties of HgTe-CdTe superlattices**

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The first theoretical calculation of the optical properties of HgTe-CdTe superlattices is presented. The envelope function method is used to obtain the superlattice band structure, and then an interpolation scheme is employed to compute \( \epsilon_\omega \), the imaginary part of a dielectric function. The major conclusion is that the optical properties of the superlattice near the band edges are such that the absorption may be comparable to or ever larger than that in the alloys.

Superlattices of HgTe-CdTe have been proposed as a novel material for application as infrared materials and experimental studies of the properties of these superlattices are now beginning. These man-made systems have the advantage of allowing us to adjust a number of the properties of the material so that the interesting features are near optimum for a given application in the infrared. The near band-edge optical properties of such superlattices are very important for the applications that are envisioned. In this letter, we report the first treatment of the near band-edge optical properties of the HgTe-CdTe superlattices.

The band-edge features for the valence band and conduction band of HgTe and CdTe are shown in Fig. 1. The valence-band edges are aligned to reflect the best estimate of the valence-band offset, and it is assumed that the valence-band offset is zero. Other important
features in this figure are that CdTe is a wide semiconductor; whereas HgTe is a symmetry-induced zero gap semiconductor. In CdTe, the states at the valence-band maximum and at the conduction-band minimum have $\Gamma_6$ and $\Gamma_8$ symmetries, respectively. However, in HgTe the states at the valence-band maximum and at the conduction-band minimum both have $\Gamma_8$ symmetry. The states of $\Gamma_8$ symmetry lie below the $\Gamma_6$ edge in HgTe. The interband optical matrix element in HgTe at $k = 0$ is given by $\langle \Gamma_8 | p | \Gamma_6 \rangle$. This matrix element, while not zero, is known to be small. The optical absorption in CdTe is governed by $\langle \Gamma_6 | p | \Gamma_6 \rangle$ which is quite large.

In the superlattice the near band-edge states are made up of predominantly $\Gamma_8$ states in the HgTe and CdTe with some admixing of the $\Gamma_6$ states. Hence, it is a very legitimate question to ask how big the optical absorption of the superlattice is in comparison to that of the Hg$_x$Cd$_{1-x}$Te alloy.

Our theoretical calculations are based upon the second-order $k\cdot p$ method with spin-orbit splitting included. Details concerning the application of a general $k\cdot p$ method to superlattices have been given elsewhere. For near band-edge absorption, Kane’s eight-band model is adequate for the present calculation.

Both solids are described by eight basis functions which include the states with $\Gamma_6$, $\Gamma_8$, and $\Gamma_8$ symmetry at the zone center. Using the above basis set, the second-order $k\cdot p$ Hamiltonian is then constructed for each solid. Some of the parameters in the Hamiltonian for each material are $E_0$, the fundamental $p$-$s$ energy gap at the $\Gamma$ point, $\Delta_0$, the spin-orbit splitting of the valence band at $\Gamma$, and $E_p$ which is related to the square of the interband momentum matrix element. The effect of other bands not included in the basis set, namely, the second-order correction, is incorporated within our model through Luttinger valence-band parameters. Following Lawaetz, we took $E_{C^{\text{CdTe}}} = 1.60$ eV, $E_{C^{\text{HgTe}}} = -0.303$ eV, $\Delta_{C^{\text{CdTe}}} = 0.91$ eV, $\Delta_{C^{\text{HgTe}}} = 1.00$ eV, $E_{C^{\text{CdTe}}} = 20.7$ eV, $E_{C^{\text{HgTe}}} = 18.0$ eV, $\gamma_{C^{\text{CdTe}}} = 5.29$, $\gamma_{C^{\text{HgTe}}} = 18.68$, $\gamma_{C^{\text{CdTe}}} = 1.89$, $\gamma_{C^{\text{HgTe}}} = 10.19$, $\gamma_{C^{\text{CdTe}}} = 2.46$, $\gamma_{C^{\text{HgTe}}} = -9.56$, $\kappa_{C^{\text{CdTe}}} = 1.27$, $\kappa_{C^{\text{HgTe}}} = 10.85$, $\epsilon_{C^{\text{CdTe}}} = 0.05$, $\epsilon_{C^{\text{HgTe}}} = 0.06$.

The lattice constants of HgTe and CdTe are not exactly the same ($d_{\text{HgTe}} = 6.462$ Å and $d_{\text{CdTe}} = 6.482$ Å). The difference in lattice constants implies that the layers in the superlattice are strained. Since experimental superlattices are frequently grown on a CdTe substrate, the lattice constant of the overall structure is that of the CdTe, and the strain is in the HgTe layers. We have made estimate of the effect of this strain in the superlattice and find that it will result in shift in energy of some of the bands by about 10 meV. However, it does not made qualitative changes in the optical properties. Hence, we have taken the strain to be zero here. The overall effects of strain will be dealt with in a future publication.

We would like to stress that second-order terms in the $k\cdot p$ Hamiltonian were used for two major reasons: (i) it restores the negative effective mass for the heavy-hole states and (ii) it provides the necessary number of bulk solutions to match the superlattice wave function and its derivative across the superlattice interfaces. The fact that the latter condition has to be realized has been recognized by White and Sham in their study of semiconductor heterostructures.

The superlattice wave functions are expanded in terms of the solutions to the bulk Hamiltonian corresponding to a given energy and wave vector parallel to the superlattice interfaces. These solutions may have either real or complex components of the wave vectors normal to the superlattice interface. In other words, all the band and gap states are included in the expansion set. Following the approximations of White and Sham, we assume that the zone-center basis functions in the two materials are linearly independent when projected onto the interface plane and that the basis functions are the same in the two materials. Both the wave func-

![FIG. 1. Energy band structure for HgTe and CdTe near the center of the Brillouin zone for HgTe-CdTe superlattices. Band offsets and symmetries of bulk states are also shown.](image1)

![FIG. 2. Predicted $\epsilon_1$ vs photon energy. The superlattice is made up of an alternating structure consisting of layers of HgTe 38.5 Å thick and layers of CdTe 38.5 Å thick. The superlattice has a band gap of 0.233 eV. For comparison, $\epsilon_1$ for the alloy of the same gap is also plotted.](image2)
Superlattices on the difference between the photon energy and the band characterized by flat subbands and high joint densities of states. The superlattice energy band structures are gap was obtained.

Virtual crystal approximation and a two-band model given folding and the reduction of spherical symmetry to itatively different from that of the bulk due to both band results of our study are presented in Figs. 2 and 3, that used by Raubenheimer and Gilat.

The results of this band structure calculation have been used to calculate \( \epsilon_2(\omega) \), the imaginary part of the dielectric function for the electric field polarized parallel and perpendicular to the interface \( \epsilon_1(\omega) \) and \( \epsilon_2(\omega) \), respectively. To compute \( \epsilon_2(\omega) \), we adopted an interpolation scheme similar to that used by Raubenheimer and Gilat.¹³

To carry out a meaningful comparison with the alloys, we have calculated the value of \( \epsilon_2(\omega) \) for the alloy by using a virtual crystal approximation and a two-band model given by Kane.⁴ An approximate square-root dependence of \( \epsilon_2(\omega) \) on the difference between the photon energy and the band gap was obtained.

The results of our study are presented in Figs. 2 and 3, we have plotted the near band-edge values of \( \epsilon_2(\omega) \) for a wide band-gap superlattice made up of 38.5-Å-thick layers of HgTe alternating with 38.5-Å-thick layers of CdTe. The resulting superlattice has a band gap at 0.233 eV. For comparison, the results for an alloy with the same band gap are shown. The important result of this calculation is that the magnitude of \( \epsilon_2(\omega) \) for the superlattice is very comparable to that of the alloy.

In Fig. 3, we present the results for a superlattice containing 70.6-Å-thick layers of HgTe and 70.6-Å-thick layers of CdTe in one unit cell. This superlattice has a small band gap equal to 0.107 eV. The exciting results are that the superlattice has optical value of \( \epsilon_2(\omega) \) that is larger than that found for the alloy.

It was found that \( \epsilon_2(\omega) \) for superlattices is small due to the small matrix element \( \langle \Gamma_\alpha | \hat{p} | \Gamma_\beta \rangle \). However, \( \epsilon_2(\omega) \) is more interesting and should have our attention.

The major conclusions of this study are that the optical properties of the superlattice near the band edges are such that the absorption may be comparable to or even bigger than that in the alloys. Further, the fact that the same band gap can be obtained for a number of different thicknesses means that it is possible to adjust the optical properties somewhat independent of the band gap.

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11. Estimates were based on the deformation potential for α-Sn [see B. J. Roman and A. W. Ewald, Phys. Rev. B 5, 3914 (1972)]. The formalism was that introduced by G. L. Bir and G. E. Pikus [Symmetry and Strain-Induced Effects in Semiconductors (Keter Publishing House Jerusalem Ltd., 1974), p. 295ff.].