Carrier-activated light modulation

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A variety of superlattices is predicted to exhibit high-speed carrier-activated light modulation. The proposal is based on the large, tunable, and very narrow absorption peak for transitions between the two lowest conduction subbands. The theory, which is demonstrated to be predictive, also suggests correspondingly large variations of the refractive index.

Recent reports have highlighted the potential importance of intersubband transitions between the two lowest conduction subbands ($C1, C2$) of a semiconductor superlattice (SL) in optoelectronic applications.[1-3] Two factors are of key significance: intersubband transitions are spectrally tunable and exceptionally strong. The VB (valence band) $\rightarrow C1$ band gap and the $C1 \rightarrow C2$ subband gap are determined independently by choice of superlattice period and alloy composition. The absorption coefficient and change in refractive index associated with the $C1 \rightarrow C2$ transitions depend directly on the number of electrons in the $C1$ subband and may be adjusted to exceed the values associated with the fundamental absorption of a direct gap bulk semiconductor. These considerations also apply to silicon-based SL's, although the effects are a factor of 10 smaller.

The carrier dependence of the intersubband optical properties is the basis of a novel class of *carrier-activated light modulators*. A light beam tuned to the miniband gap energy propagates through an undoped superlattice without appreciable attenuation since there are no carriers in the $C1$ subband. If, however, the beam is polarized perpendicular to the superlattice planes (the z direction) and electrons are electrically injected into or optically generated within the superlattice, the beam can be modulated by the induced intersubband absorptive and/or refractive effects. In view of the polarization restriction, carrier-activated modulation is most simply realized in integrated optical configurations where the light signals are guided by planar waveguide channels aligned parallel to the planes of the superlattice. One particularly promising configuration, which would be useful in communications and computer applications, is that of a crossed waveguide switch wherein the cross-channel coupling is controlled by carrier-activated index changes at the intersection of waveguides.[4,5] A second promising configuration, which would be useful in signal processing applications, is that of a one-dimensional spatial modulator wherein a planar beam is diffracted by an induced spatially varying carrier distribution within the planar channel.[6] Picosecond response of these modulators is expected if the electrons are electrically injected normal to the superlattice planes by resonant tunneling. The response of optically activated devices would be limited to the nanosecond range by carrier recombination, but the independent tunability of the VB $\rightarrow C1$ band gap makes possible three-dimensional stacking of switching structures in which the signal at a given level is controlled by a light distribution propagating normal to the superlattice and tuned to the band gap at that level. The analysis that follows demonstrates that useful carrier-activated modulation is possible under practicable circumstances.[7]

These considerations are firmly based on the theoretical envelope function description of superlattices which has previously yielded quantitative results for effective masses and oscillator strengths in 3-5 and 2-6 superlattices.[8] The optical absorption is equally well described. As shown in Fig. 1 for the InAs/GaSb type II SL, the results, which depend only on input pertaining to the bulk parent compounds within the Kane model, (1) agree as well with experiments as Kane's original calculations for bulk InSb and (2) provide a quantitative description of the structure due to both VB $\rightarrow C1$ and $C2$ transitions. Similar quantitative results have been obtained for HgTe/CdTe and GaAs/GaAlAs superlattices. The illustration presented here provides a particularly stringent test since the VB envelope functions peak in the GaSb layers, whereas those associated with the conduction bands peak in the InAs layers. This effect leads to relatively low values of $\alpha(E)$, where E is the photon energy. Formal difficulties connected with satisfying envelope function boundary conditions at the interface, when the bulk band structure used as input is limited to only those bands considered in the Kane model, have been shown to have very small numerical effects. These considerations provide confidence that the present theoretical approach is indeed predictive.

Figure 2 shows the $C1 \rightarrow C2$, $K = 0$ gap $E_g^{C2,C1}$, the corresponding oscillator strength $f_{C1,C2}^{\perp} = (2/m)$
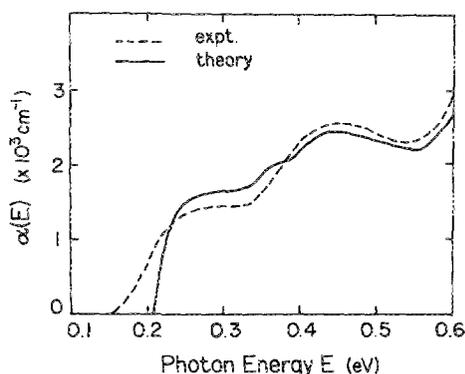

FIG. 1. Comparison of experimental (dashed line) of Chang *et al.* (see Ref. 9) and theoretical (solid line) fundamental absorption coefficients $\alpha(E)$ as function of photon energy E for 37 Å InAs/37 Å GaSb at $T = 4$ K. The theory contains only bulk input parameters.

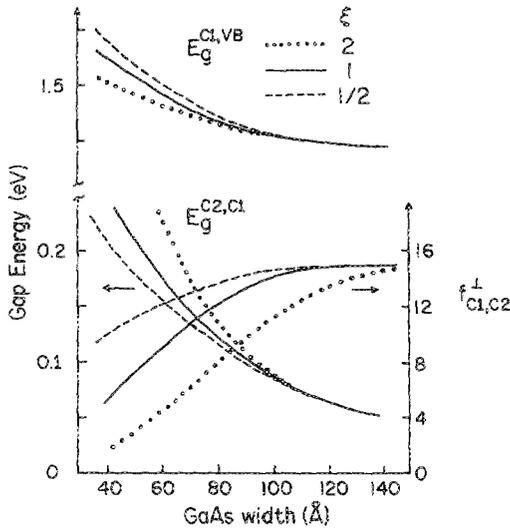[a] To whom all correspondence should be addressed.

FIG. 2. Calculated VB $\rightarrow C1$ fundamental superlattice band gap $E_g^{C1,VB}$ and $C1 \rightarrow C2$ subband gap $E_g^{C2,C1}$ vs GaAs layer width for GaAs/$Ga_{0.7}Al_{0.3}$As superlattice having 300 K bulk parameters. Relative layer widths are specified by ratio $\xi = $ (GaAs width)/($Ga_{0.7}Al_{0.3}$As width) $= 2$ (dotted), 1 (solid), and 1/2 (dashed). Corresponding oscillator strengths $f_{C1,C2}^\perp$ are given on the right-hand scale.
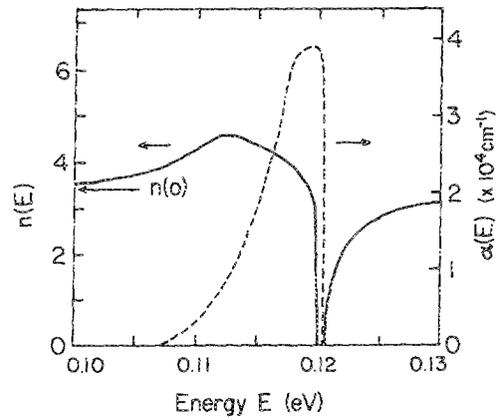

FIG. 3. Calculated refractive index $n(E)$ (solid line; left-hand scale) and absorption coefficient $\alpha(E)$ (dashed-line; right-hand scale) vs photon energy E for 80 Å GaAs/160 Å $Ga_{0.7}Al_{0.3}$As at $T = 300$ K, for $C1$ electron concentration $n_{C1} = 5 \times 10^{17}$ cm^{-3}.

$\times |\langle C2,0|p_\perp|C1,0\rangle|^2/E_g^{C2,C1} \cong E_P/E_g^{C2,C1}$, and the SL band gap $E_g^{C1,VB}$ as a function of GaAs layer width l_{GaAs} for three width ratios $\xi = l_{GaAs}/l_{GaAlAs}$, where l_{GaAlAs} is the width of $Ga_{0.7}Al_{0.3}$As layers. The matrix element of $p_\perp$ refers to light polarized along the z direction. Layer width adjustment leads to a $E_g^{C2,C1}$ tunability extending from 0.05 eV (25 μm) to 0.2 eV (6 μm). This fact suggests that the infrared band-aligned SL lattice suggested by Yuh and Wang[3] is more practically achievable by adjusting layer widths than by well shaping. The limiting oscillator strength is ~ 15 (in agreement with the estimates of West and Eglash[1]) and is greater than the value ~ 10 associated with the fundamental optical absorption. The decrease of $f_{C1,C2}^\perp$ with decreasing l_{GaAlAs} reflects the diminished effectiveness of the barriers as they become thinner. Similar effects are found in related superlattices. The value of $f_{C1,C2}^\perp$ for HgTe/CdTe and InAs/GaSb of comparable thickness is similar to that found in GaAs/GaAlAs.

For $l_{GaAs} = 80$ Å and $\xi = 1/2$, we find E_P is 1.6 eV for $C1 \rightarrow C2$ compared to the fundamental absorption value VB$\rightarrow C1$ of 15 eV; however, the ratio $E_g^{C1,VB}/E_g^{C2,C1} = 12.3$ more than compensates for this reduction in $f_{C1,C2}^\perp$. The size of $f_{C1,C2}^\perp$ together with the large joint density of states, due to the fact that $C1$ and $C2$ are nearly parallel and form critical surfaces along the $\parallel$ direction, leads to an exceptionally large optical absorption coefficient $\alpha(E)$. The two-dimensional joint density of states $m_{r,\parallel}/\pi\hbar^2 d$ is constant and proportional to the reduced mass $m_{r,\parallel}^{-1} = m_{C1,\parallel}^{-1} - m_{C2,\parallel}^{-1}$ which is large (d is the SL period). We find $m_{C1,\parallel} = 0.066m$ and $m_{C2,\parallel} = 0.074m$, $m_{r,\parallel} = 0.61m$, and $\alpha(E) \approx 4 \times 10^4$ cm^{-1} when the $C1$ filling corresponds to $n_{C1} = 5 \times 10^{17}$ cm^{-3} (Fig. 3). At $T = 0$ K the range for which $\alpha(E)$ is nonvanishing is $E_g^{C1,C2}$ ($k = 0$) $> E > E_g^{C1,C2}(k = k_F)$, where k and k_F, the Fermi wave vector, are parallel to the planes. Because

of the near parallelism of the $C1,C2$ bands, the linewidth ΔE for which $\alpha(E)$ is nonzero is *very narrow*. Specifically, $\Delta E = (10^{-20} n)$ eV, where n is the carrier concentration (e.g., 0.005 eV for $n = 5 \times 10^{17}$ cm^{-3}). Temperature effects, causing broadening of the electron distribution and $\alpha(E)$, are small for the same reason. The index of refraction $n(E)$ and $\alpha(E)$, corresponding to $T = 300$ K and $n_{C1} = 5 \times 10^{17}$ cm^{-3}, which specify the optical constants completely, are shown in Fig. 3. The total absorption width of 0.01 eV is comparable to semiconductor laser widths.

Figure 3 also shows that the value of $n(E)$ below the absorption peak, which is nearly the same as $n(0)$ when $C1$ is unpopulated, is significantly larger (~ 0.6) than the value above the peak. This variation suggests that the current and optical power requirements for refractive applications are modest. To switch a beam in a cross waveguide configuration by carrier activation requires a minimum injection current of order 10μA (i.e., a current density of 10 A/cm^2) or a light input of 10 μW.

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