Effect of thermally induced charged-carrier transfer on near-infrared intersubband transitions in $In_xGa_{1-x}As/AlAs/Al_yAs_{1-y}Sb/InP$ coupled quantum-well structure

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We have investigated the near-infrared intersubband transition (ISBT) influenced by thermally induced charged-carrier transfer in strongly coupled $In_xGa_{1-x}As/Al_yAs_{1-y}Sb$ quantum-well structures lattice matched to InP substrates. We have compared the ISBT's in symmetric and asymmetric coupled quantum-well structures by investigating the temperature-induced change in the carrier distribution in the subband states. Qualitatively different behavior is found in symmetric and asymmetric coupled quantum-well structures. In these structures, the change in the built-in dc space-charge electric field due to charged carrier transfer results in a blueshift of the ground to the first excited state ISBT with increasing temperature. This blueshift along with the associated redshift of the higher excited state ISBT on increasing the temperature is larger in near-symmetric structures indicating a stronger coupling between the adjacent wells compared to the asymmetric structures. The thermal stability of ISBT in coupled structures is more compared to that in single quantum wells. The interface quality significantly affects the ISBT energy in these structures.

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Intersubband transitions in semiconductor quantum wells have been attracting much attention in various infrared optoelectronic device applications such as semiconductor lasers,[1,2] detector,[3] and ultrafast all-optical modulators and switches.[4,5] Due to the nature of unipolar carrier relaxation process involved, intersubband transitions are extremely fast with a large transition dipole moment and can be tuned independently of the band gap of the material by controlling the width and the coupling of the quantum-well structures (QW's). This has led to the search for the development of a suitable material system for ultrafast multi-wavelength all-optical switching devices for future optical communication systems. A large band offset between the well and the barrier material is a prerequisite to achieve communication wavelength intersubband transitions. In principle this can be obtained either in InP systems using $In_xGa_{1-x}As/AlAs$ or $In_xGa_{1-x}As/Al_yAs_{1-y}Sb$ quantum-well structures[3–6] or GaN-based AlGaN/GaN systems.

Near-infrared intersubband transition (ISBT) below 2 μm can be achieved in single quantum-well structures (QW's) using either strained $In_xGa_{1-x}As/AlAs$ QW's grown over GaAs substrates[6] or lattice matched $In_xGa_{1-x}As/Al_yAs_{1-y}Sb$ QW's grown over InP substrate.[7] However, for the communication wavelength regime ($\sim$1.3 μm–1.55 μm) the coupled quantum well concept has inherent advantages due to its flexibility in tailoring quantized energy levels and carrier relaxation processes.[5] Due to larger optical nonlinearity in coupled quantum-well structures, we have also recently observed a subpicsecond relaxation rate which is comparatively faster than the 1–3 ps response in single $In_xGa_{1-x}As/Al_yAs_{1-y}Sb$ QW structures.[8]

In these coupled quantum-well structures, the intersubband optical characteristics including the carrier relaxation rate and absorption characteristics depends significantly on the sheet density of the carriers in the conduction subband states. The extrinsic doping of the QW layers as well as the temperature of the system can influence the population of the subband states. In high bit rate optical communication systems, as thermal nonlinearities caused by carrier accumulation significantly affects the performance of a device such as an optical switch, the effect of thermal processes on the intersubband transitions needs to be investigated. The depletion of carriers from the ground subband state due to the rise in temperature can lead to an increase in the threshold pump intensity for optical switching other than an induced change in the transition wavelength. Furthermore, in strongly coupled QW's thermally induced charge-carrier transfer between subbands modifies the charge distribution of the carriers between wells. This leads to a modification of the built-in dc space-charge electric field in the structure and consequently the confinement potential of the carriers.[9] Moreover, as the generation of near-infrared intersubband transition requires very thin quantum-well and barrier width comparable to the interface roughness, this thermal process is expected to severely modify the subband energies and envelope states of the structure.

The purpose of this work is to demonstrate the onset of thermally induced charged carrier transfer influencing intersubband transitions in coupled quantum-well structures. It also provides a technique for the temperature tuning of intersubband transition in the communication wavelength regime. We also compare the intersubband transitions in symmetric and asymmetric quantum-well structures.

We have designed both symmetric coupled double QW's (SCDQW) with identical well width and asymmetric structure (ACDQW) with different well width to achieve intersubband transition in the 1.55μm region. The double wells in both symmetric and asymmetric structures are coupled strongly by a thin central barrier material of identical width ($\sim$1 nm). $In_{0.53}Ga_{0.47}As-AlAs_{0.56}Sb_{0.44}$ coupled double quantum-well structures were grown over semi-insulating InP substrates by molecular beam epitaxy. The asymmetric structure was designed to be consisting of two different

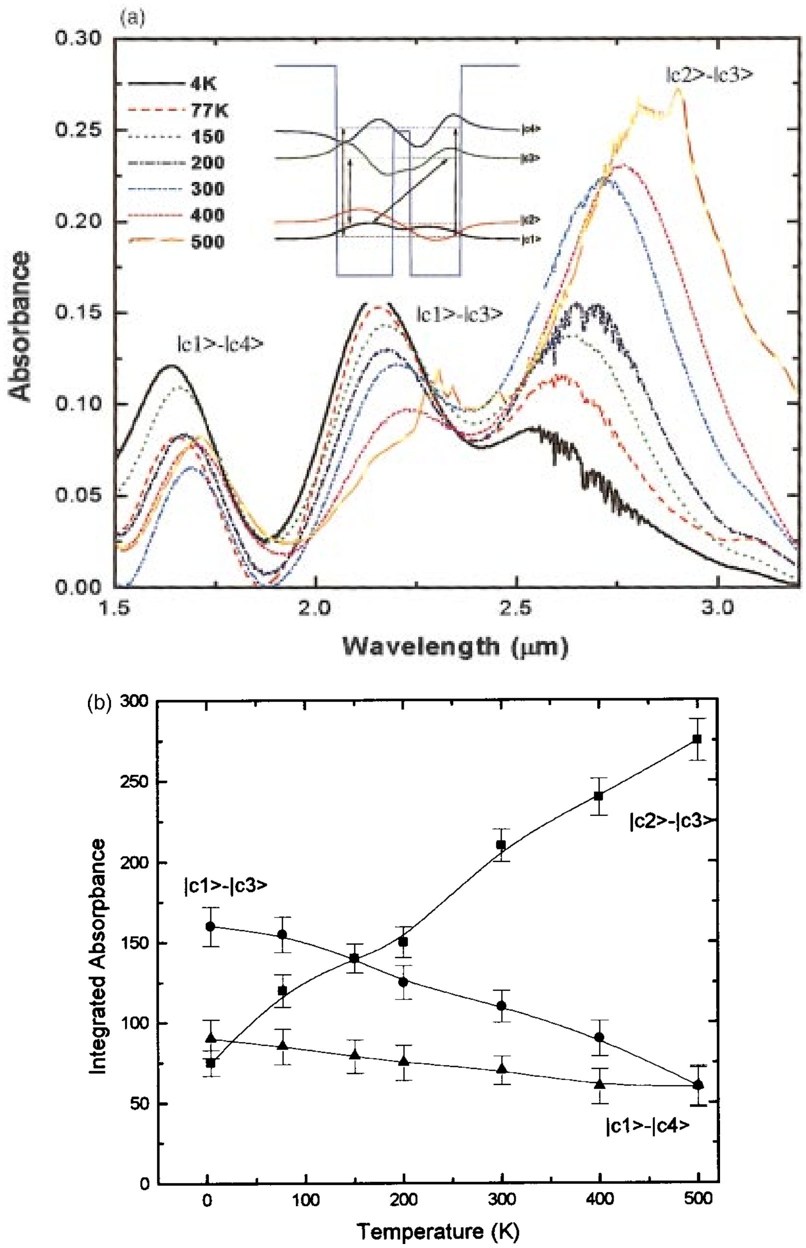

FIG. 1. Color (a) Intersubband absorbance spectra of symmetric coupled quantum well [$Al_xAs_{1-x}Sb$(10 nm)/InGaAs (2.8 nm)/AlAs (1 nm)/$In_xGa_{1-x}As$ (2.6 nm)/$Al_xAs_{1-x}Sb$(10 nm)] at various temperatures. (b) Temperature dependence of integrated absorbance in SCDQW, $|c1\rangle$-$|c4\rangle$ transition (▲), $|c2\rangle$-$|c3\rangle$ transition (■) and $|c1\rangle$-$|c3\rangle$ transition (●).

$In_{0.53}Ga_{0.47}As$ wells of width 2.1 nm and 3 nm coupled together by a central barrier of AlAs of 1.0 nm and bound by an outer barrier layer of 10 nm of $AlAs_{0.56}Sb_{0.44}$. The symmetric structure composed of two 2.7 nm $In_xGa_{1-x}As$ wells, with a 1.0 nm central barrier of AlAs and an outer barrier of 10 nm with 100 periods, was grown. In both the structures the $In_xGa_{1-x}As$ layers were uniformly Si doped to $n=1\times10^{19}\,cm^{-3}$ grown with a 100 nm buffer layer of $AlAs_{0.56}Sb_{0.44}$ and a 10 nm cap layer of $In_yAl_{1-y}As$. The samples of about 5 mm long were cleaved and its two edge facets were polished into 45° wedges for multiple-reflection waveguide geometry in order to enhance the ISB absorption. The sample was mounted on the cold finger of a He flow optical cryostat (Oxford) with Sapphire windows. The micro-cryostat had a built-in heater and a temperature diode sensor that allows a continuous variation and detection of the crystal temperature in the 4–500 K temperature range. The infrared spectra were measured using a Fourier transform infrared spectrometer (Bruker IFS-66 v/s) with InSb detector and a wire-grid polarizer. The absorbance spectra [$=-\ln(T_\perp'/T_\parallel')$] were measured and deduced from the intersubband selection rules.

Figure 1(a) shows the absorbance spectra from the SCDQW structure at various temperatures. Three resonance intersubband absorption peaks were observed in the near-infrared wavelength regime spanning from 1.00–3.5 μm that can be attributed to the $|c1\text{-}c4\rangle$, $|c1\rangle$-$c3\rangle$, and $|c2\rangle$-$|c3\rangle$ transitions. Unlike in conventional $Al_xGa_{1-x}As$/GaAs QW

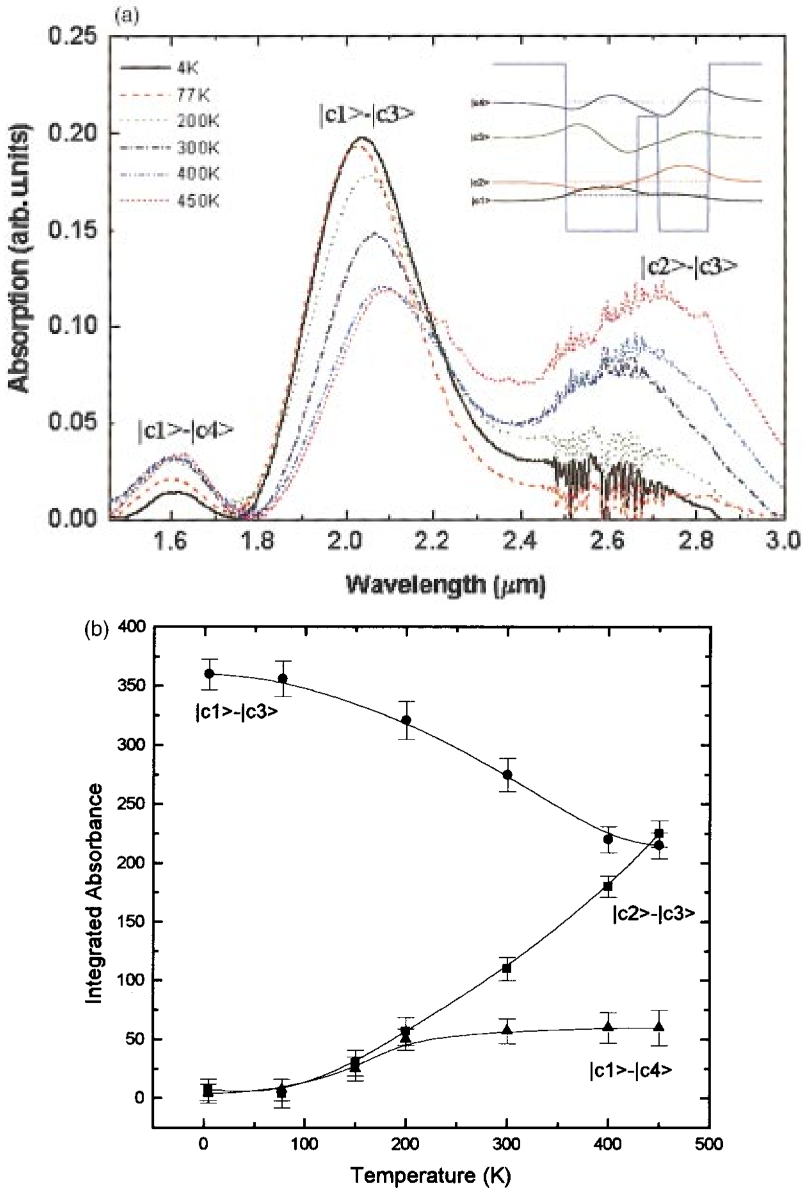

FIG. 2. Color (a) Intersubband absorbance spectra of asymmetric coupled quantum well [$Al_xAs_{1-y}Sb$ (10 nm)/$In_xGa_{1-x}As$ (3 nm)/AlAs (1 nm)$In_xGa_{1-x}As$ (2.1 nm)$Al_xAs_{1-y}Sb$ (10 nm)] at various temperatures. (b) Temperature dependence of integrated absorbance in AS-CDQW; $|c1\rangle$-$|c4\rangle$ transition (▲), $|c2\rangle$-$|c3\rangle$ transition (■) and $|c1\rangle$-$|c3\rangle$ transition (●).

system, the optical properties are strongly modified in Sb QW system due to group-V species interchange induced by the various radiative centers and trap at the $In_xGa_{1-x}As/Al_yAs_{1-y}Sb$ hetero-interface.[13,14] Sb alloying in the well layers lead to the formation of $In_xGa_{1-x}As_ySb_{1-y}$, which can be comparable to the central barrier thickness varying from 0.5–3 ML.[14] In such cases, we may expect the modification of the band-lineup due to electrostatic band ending that increases with increasing electron concentration. Recent secondary ion mass spectroscopy data on these structures reveal that group-III interdiffusion also increases with increasing doping concentration.[15] The intermixing at the interface results in fluctuations of the actually grown well-width resulting in a slight asymmetricity of the grown structure [shown in the inset of Fig. 1(a) with a half-monolayer well-width fluctuation].[14] The grown structure appears to be slightly asymmetrical, which allows the normally forbidden transition between the states ($|c1\rangle$-$|c3\rangle$).[5] It is further observed that the activation of dopant within the InGaAs layers is sufficiently high to exhibit ISB transitions from the second subband state at 4 K. In Fig. 1(b). We have plotted the integrated absorbance of the intersubband absorbance in the near-infrared regime (associated with $|n\rangle$-$|m\rangle$ transitions).[10] It has been also assumed that the dominant contribution of the temperature dependence of the thermally assisted ISBT's comes from the changes in the carrier density rather than the oscillator strength. The $|c2\rangle$-$|c3\rangle$ transitions reduces with the decrease of temperature as the population of thermally excited carriers in the state $|c2\rangle$ is drastically reduced at low temperatures. The carriers are expected to accumulate at the ground subband state $|c1\rangle$ at lower temperature providing more carriers for intersubband transition. This is also reflected in the enhancement of the ISBT absorption involving the ground subband state ($\alpha_{|c1\rangle\text{-}|c4\rangle}$ and $\alpha_{|c1\rangle\text{-}|c3\rangle}$) on reducing the temperature.

In Fig. 2(a) we have plotted the temperature dependence of the ISBT spectra in the asymmetric well structure shown in the inset, including half-monolayer well-width fluctuation for comparing the results with the actually grown structure. The extent of the asymmetricity in the coupled QW structure can be resolved from the magnitude of the ISBT absorption due to the $|c1\rangle$-$|c3\rangle$ transition compared to the $|c1\rangle$-$|c4\rangle$ transition. On comparing Fig. 1(a) and Fig. 2(a), the asymmetricity in the later structure is clearly observed. The $|c2\rangle$-$|c3\rangle$ absorption peaks tends to disappear at lower temperatures. From the temperature dependence of the integrated absorbance as plotted in Fig. 2(b). it can be seen that though the intersubband absorption characteristics $\alpha_{c1\rangle\text{-}|c3\rangle}$ and $\alpha_{|c2\rangle\text{-}|c3\rangle}$ in the asymmetric structures are similar to the near-symmetric structure, the $\alpha_{|c1\rangle\text{-}|c4\rangle}$ transition reduces with the decrease in temperature. The temperature dependence of intersubband absorption spectra in ACDQW structure shows that the interwell coupling is affected by the variation in temperature (in other words the thermally induced shifts in the transition energies and in the enveloped states also are significant in addition to the changes in carrier density of thermally populated subbands).

In Fig. 3(a) we have compared the temperature-induced shift of the resonance $|c1\rangle$-$|c4\rangle$, $|c2\rangle$-$|c3\rangle$, and $|c1\rangle$-$|c3\rangle$ISBT transition energies in symmetric and asymmetric structures. The $|c1\rangle$-$|c4\rangle$ transition in the ACDQW is nearly independent of the temperature change compared to the large redshift of nearly 40 meV in SCDQW. It is also observed that the symmetric coupled DQW structures exhibits a larger redshift in the resonance $|c1\rangle$-$|c4\rangle$ and $|c2\rangle$-$|c3\rangle$ISBT energies compared to ASDQW structures, with increasing temperature. However in both these structures there is a larger redshift observed for the $|c2\rangle$-$|c3\rangle$ transition as compared to the redshift for the $|c1\rangle$-$|c3\rangle$ transition. From these measurements the temperature shift of the $|c1\rangle$-$|c2\rangle$ISBT can be deduced by subtracting the two transition energies. There is a large blueshift of the $|c1\rangle$-$|c2\rangle$ISBT of about 25 meV in SCDQW structures and 10 meV in ASDQW for temperatures varying from 4–500 K, as shown in Fig. 3(b). The diffusion of Sb into the quantum-well layers leads to the formation of quaternary InGaAsSb layers at the interface and results in the formation of interface states that has been observed from ISBT's in single quantum-well structures.[11] From the theoretical estimation of the self-consistent Schrödinger-Poisson equations for the given structures we have observed that due to the induced asymmetricity owing to well-width fluctuation, the carriers at low temperatures are localized in the wider well of the coupled quantum well resulting in a band bending. With the increasing temperature, more carriers are transferred into the interface states and also to narrower QW's, giving rise to a weaker dc field along the whole period. This weaker space-charge field induces a blueshift of the $|c1\rangle$-$|c2\rangle$ transition energy and a redshift of the $|c2\rangle$-$|c3\rangle$ transition energy since the second subband is expected to be pushed up with decreasing space-charge field. This is also associated with the

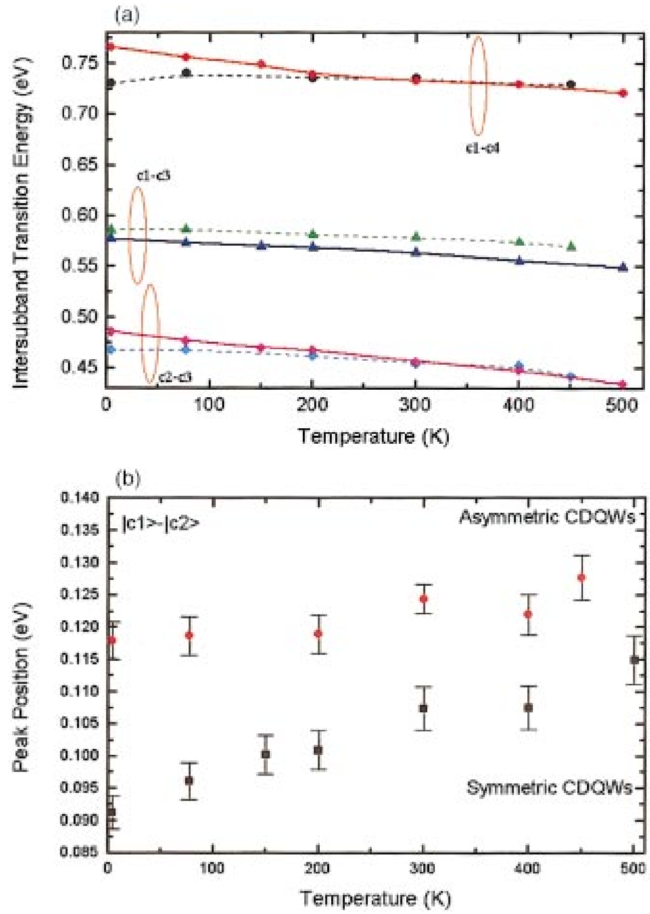

FIG. 3. Color (a) Comparison of temperature induced shift in ISBT energy in symmetric (——) and asymmetric (· · · ·) CDQW structure. (b) The center peak position of the $|c1\rangle$-$|c2\rangle$ transition energy (●) asymmetric CDQW structure, (■) symmetric CDQW structure.

fact that the space-charge field would have a smaller influence on the $|c1\rangle$-$|c3\rangle$ISBT transition, since both envelopes of this transition are localized in the wider well of the coupled quantum-well structures. The $|c1\rangle$-$|c4\rangle$ transition in the ASDQW is also relatively insensitive to the temperature change as the $|c4\rangle$ transition is not confined within one particular well in the coupled well structures. The temperature induced redshift in the $|c1\rangle$-$|c4\rangle$ transition in ASDQW is 2.5×10^{-4} meV/K compared to 0.1 meV/K in the SCDQW and 0.216 meV/K in bulk InGaAs material in the communication wavelength regime.[12] The relative temperature insensitiveness of ISBT's in ASDQW is important for application with high stability compared to interband transition-based optical devices such as electro-optic modulators or quantum-well lasers. This is also an advantageous characteristic for the design and fabrication of near-infrared intersubband cascade lasers based on asymmetric coupled quantum-well structures.

The spectral analysis of ISBT's in single QW's reveal that the transition energy and absorption linewidths are dominated by the inhomogeneous broadening owing to the interface quality influenced by interface roughness and compositional variation due to the interdiffusion of group-III and group-V species between the well and the barrier interface.[16] The effect of exchange interaction and nonparabolicity is trivial compared to the influence of the interface. The temperature dependence of the ISBT energy due to nonparabolicity in a single quantum well is just 3 meV in the range $0\,\mathrm{K}<T<450\,\mathrm{K}$, whereas the exchange interaction accounts for less than 1.5 meV within the same range. It has been observed that, in single QW's, due to interface related change in band-lineup of the system, the subband states near the top of the conduction band are more susceptible to the change in temperature, resulting in a larger temperature coefficient in narrower wells. The induced strain and the changes in the interface-dipole contribution to the band-offset due to intermixed layers eventually affect the energy band structure in a much more complicated way. The expected weak Stark shift in the SCDQW is affected by the temperature dependence of the carriers in its relatively narrower QW's (~2.6 nm) compared to that in the ASDQW where the dominant transitions are localized in the wider (~3.1 nm) QW and the temperature induced redshift is offset by the interface-related blueshifts.

In summary, we have investigated the temperature dependence of intersubband transitions in symmetric and asymmetric coupled quantum-well structures. We observed a large thermally induced shift in intersubband transition energies—larger than the LO phonon energy. The space-charge field and population of the second subband vary with temperature. The shift in ISBT energy in ASDQW structure is relatively less sensitive to the change in temperature compared to SCDQW or uncoupled multiple QW's. The coupled QW structures offers a better stability in the communication regime compared to uncoupled or interband optical devices. In this paper we have demonstrated that the ISBT energy and absorption coefficient in the near-infrared regime can be manipulated by thermal excitation of the charge carriers and therefore the above investigation is essential for a proper design and operation of all-optical multiwavelength switch.

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