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Peak-to-zero modulation of optical absorption via electrically controllable quantum interference

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We propose a modulation scheme of optical absorption in a coupled asymmetric quantum well (QW) structure via electrically controllable quantum interference. It is based on the parallel-perpendicular energy coupling effect. We show that by applying an external electric field in the parallel direction (to the QW layers), we can obtain a maximum (peak-type) absorption at a specific wavelength where absorption cancellation would occur due to electrically induced transparency without such an external field.

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Quantum interferences between quantum-mechanical paths have been a subject of active study over the last decade. Some of many examples for using these interferences include electromagnetically induced transparency (EIT) [1], lasers without inversion (LWI) [2], and highly efficient schemes for nonlinear optics [3]. Recently, optical devices such as intersubband laser without a population inversion [4] or nonlinear optical elements sharply reducing the absorption [5] based on the interference between intersubband transitions in coupled quantum wells (QW) have been proposed [6]- [10]. Intersubband transitions had already received much attention due to the possibility of being an interesting and new class of optical devices, even before the introduction of quantum interference to them - i. e. quantum cascade lasers [11] and QW infrared photodetectors [12,13]. Therefore, we hope that a number of newer and innovative optical devices will be available and will be found useful with the application of quantum interference to intersubband transitions in QW's. In this report, we apply this interference between intersubband transitions to a QW optical modulator and propose a modulation scheme of optical absorption by controlling the parallel momentum of electrons (i. e. by parallel electric fields) in a coupled asymmetric QW structure.

Our scheme is based on the parallel-perpendicular energy coupling effect [14]- [17]. In heterostructures with spatially varying effective masses, the conservation of parallel momentum at a heterojunction brings a loss or gain of kinetic energy in that direction, and the energy difference is conferred on the perpendicular kinetic energy. Therefore, the perpendicular (i. e. confined) energy levels and corresponding wavefunctions are dependent on, and hence, can be modified by the parallel momentum (i. e. parallel kinetic energy) of electrons. These parallel-momentum dependent characteristics of QW structures are successfully applied to the implementation of electrically induced transparency by the present authors [10].

Based on this energy coupling effect, we propose a coupled asymmetric QW structure in Fig. 1 which has the feasibility of peak-to-zero modulation of optical absorption. The materials and parameters assumed in this work are shown in Table 1. This structure can be grown by molecular-beam epitaxy (MBE) on a

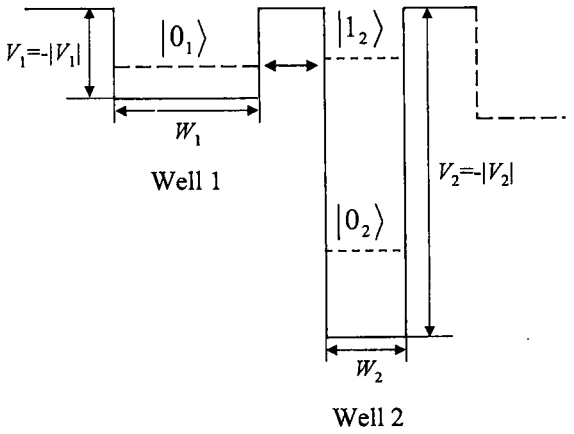

FIG. 1. Schematic diagram of proposed structure. Materials and parameters can be found in Table 1.

TABLE 1. Materials and parameters of the proposed QW structure.

	Well 1	Well 2	Barrier
Material	$Al_{0.42}Ga_{0.58}As$	GaAs	$Al_{0.54}Ga_{0.46}As$
Potential Depth($\|V\|$)	120 meV	540 meV	0
With(W)	6.8nm	4.2nm	2.0nm(thin barrier)
Effective Mass(m^*)	$0.102m_0$	$0.067m_0$	$0.112m_0$

semi-insulating GaAs substrate by following the similar methods suggested in Refs. [8], [9]. They are carefully determined to make the eigenenergies (assuming isolated QW's) of the ground state of well 1 ($|0_1\rangle$) and the first excited state of well 2 ($|1_2\rangle$) be nearly the same while the overall ground state of this asymmetric QW ($|0\rangle \approx |0_2\rangle$) is separated with a large band splitting. Therefore, $|0_1\rangle$ and $|1_2\rangle$ should be mixed (that is, quantum mechanical anticross) with each other through coherent tunneling across a thin barrier region between the two QW's, and create $|1\rangle$ and $|2\rangle$. On the left-hand side of well 1, there is a very thick (ideally infinite) barrier which suppresses any tunneling of all electrons. On the right-hand side of well 2, there is a thin barrier which allows tunneling of electrons in states $|1\rangle$ and $|2\rangle$ with tunneling probability of $1/\tau$. However, it suppresses any tunneling of electrons in stte $|0\rangle$. Since $|1\rangle$ and $|2\rangle$ are strongly coupled to a continuum, they should be regarded as continuum resonances with a linewidth dominated by the tunneling probability through the thin layer [9]. The coherence of coupled states is guaranteed by coupling through coherent tunneling across a narrow barrier region [4] and thus, we need not to have an external lightwave as in case of the EIT.

In the proposed structure, there are two dominant resonance (absorption) peaks ($|0\rangle \rightarrow |1\rangle$ and $|0\rangle \rightarrow |2\rangle$). By using tight-binding approximation, the transition matrix elements z_{01} (for $|0\rangle \rightarrow |1\rangle$) and z_{02} (for $|0\rangle \rightarrow |2\rangle$) can be written as $z_{01} = \langle 1_2|1\rangle z_{01}^{(2)}$ and $z_{02} = \langle 1_2|2\rangle z_{01}^{(2)}$ (where $z_{01}^{(2)}$ ($=\langle 0_2|z|1_2\rangle$) is the transition matrix element of well 2 computed for the isolated well and $|0\rangle \approx |0_2\rangle$ is assumed) [10]. The transition matrix element from $|0\rangle$ to a quasi-continuum state $|c\rangle$ (which is formed by the coupling of $|1\rangle$ and $|2\rangle$ to a continuum through tunneling across a thin layer) can be written as a sum of z_{01} and z_{02} with appropriate weighting values. Therefore, z_{0c} consists of two terms which interfere destructively (note that the sign of $\langle 1_2|1\rangle$ (thus that of z_{01}) is opposite to that of $\langle 1_2|2\rangle$ (thus that of z_{02}); see Fig. 2(a)). For a complete cancellation of absorption, $\langle 1_2|1\rangle$ must be nearly equal to $-\langle 1_2|2\rangle$. This is guaranteed by designing the eigenenergies of $|0_1\rangle$ and $|1_2\rangle$ nearly equal and thus, by making $|0_1\rangle$ and $|1_2\rangle$ be mixed to generate $|1\rangle$ and $|2\rangle$. Note that if their eigenenergies are equal, $|1\rangle$ and $|2\rangle$ can be approximated as $(1/\sqrt{2})[|0_1\rangle \pm |1_2\rangle]$, respectively, and in this case $\langle 1_2|1\rangle = -\langle 1_2|2\rangle$. Thus we can get an absorption cancellation (or suppression of optical absorption) between two resonance absorption peaks.

These are the accounts when the parallel momentum of electrons is small. However, if it gets larger, the eigenenergies of $|0_1\rangle$ and $|1_2\rangle$ are no longer equal. If the eigenenergy of $|1_2\rangle$ gets higher than that of $|0_1\rangle$, $|\langle 1_2|1\rangle|$ becomes smaller than $|\langle 1_2|2\rangle|$ and vice versa. If any of them ($|\langle 1_2|1\rangle|$ and $|\langle 1_2|2\rangle|$) is sufficiently smaller than the other, we can say that there is effectively only one transition (that of $|0\rangle \rightarrow |1\rangle$ or $|0\rangle \rightarrow |2\rangle$). Thus we can get an effectively single absorption peak. If we design such that this effective absorption peak occurs at the zero absorption wavelength (between two resonance peaks) when the parallel momentum is small, then we can say that initially (with $k_r = 0$ where k_r denotes the parallel wavevector of electrons) there exists zero absorption (absorption cancellation) and however, when the electrons get enough parallel kinetic energies, peak absorption occurs at the energy value where absorption cancellation occurred.

We assume that we can change the parallel kinetic energy or momentum of electrons, and thus we can select zero absorption or peak absorption at the specific wavelength (that is, we can modulate optical absorption) electrically by exerting parallel electric fields. The feasibility and detailed discussion on this method was already published in Ref. [15].

The parallel kinetic energy makes the eigenenergy levels of $|0_1\rangle$, $|0_2\rangle$, and $|1_2\rangle$ increase (so do those of $|0\rangle$, $|1\rangle$, and $|2\rangle$) and the energy differences between $|0\rangle$ and $|1\rangle$, and $|0\rangle$ and $|2\rangle$ decrease in AlGaAs QW structures [18]. Therefore, if we want to, by exerting an external parallel electric field, make effectively single absorption peak occur between two original resonance wavelength points when the parallel momentum is small (at zero absorption wavelength), we have to make the absorption occur dominantly at $|0\rangle \rightarrow |2\rangle$ transition. This means we have to design such that, when the parallel momentum is large, the eigenenergy of $|1_2\rangle$ gets higher than that of $|0_1\rangle$ and thus, $|\langle 1_2|2\rangle|$ becomes sufficiently larger than $|\langle 1_2|1\rangle|$. This is possible since in AlGaAs structures, electrons are effectively 'heavier' where potentials are deeper [19].

To see this effect quantitatively, we calculated the

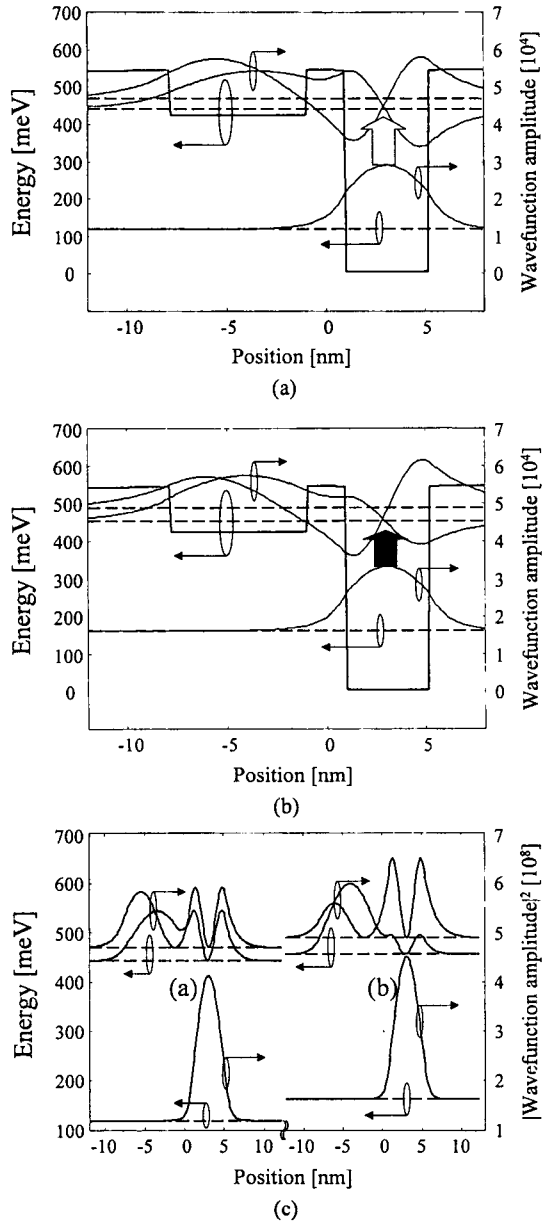

FIG. 2. Calculated electronic wavefunctions when (a) $E_{k_r} = 0$ and (b) $E_{k_r} = 70$ meV, and (c) their squared moduli. Materials and parameters can be found in Table 1.

electronic wavefunctions with (a) $E_{k_r} = 0$ meV and (b) $E_{k_r} = 70$ meV (where E_{k_r} denotes the parallel kinetic energy of electrons), and showed them in Fig. 2. In the above calculations, we let the arbitrary phase factor of the wavefunctions such that inside the left (infinitely thick) barrier of the left well (well 1), they are positive for all energies [9,10]. The detailed calculation procedure can be found in Ref. [10]. From these figures, we can say that initially with $k_r = 0$, we can expect destructive interference (suppression of optical absorption) between the two resonance absorption peaks since $|\langle 1_2|1\rangle| \approx |\langle 1_2|2\rangle|$ (see Fig. 2(c)). When k_r is increased (corresponding to the kinetic energy of 70 meV) enough to make the effective potential depth change sufficiently, effectively one absorption occurs since $|\langle 1_2|2\rangle| \gg |\langle 1_2|1\rangle|$ (also see Fig. 2(c)). This means we can modulate the optical absorption by controlling the parallel momentum of electrons.

To see this effect more clearly, we plotted intersubband absorption coefficients (a) without a parallel electric field and (b) with an electric field in Fig. 3. Application of a parallel electric field will cause a broad distribution of electrons in parallel kinetic energy. We take account of this broad distribution as is detailed in Ref. [10]. We approximated the broad distribution of electrons in parallel kinetic energy as a Gaussian distribution function with mean value $E_{t0} =$ 62 meV and the standard deviation σ_t =15 meV. Broadening factor (linewidth, ΔE_{FWHM}) is given as $\Delta E_{FWHM}/2 \equiv \hbar/\tau$ where $1/\tau$ is the tunneling escape rate. Tunneling is treated phenomenologically using tunneling rates typical for multiquantum wells [10]. We note that any scattering process which can induce abrupt change in an electron's phase must be suppressed to guarantee the *coherence* and *interference* of an electron's wavefunction. This restriction for the coherence of the electron's wavefunction is required for all devices based on quantum interference and is one of the most challenging problems for the actual implementation of practical devices. Therefore, the background doping density must be relatively small and the operating temperature should be significantly low [7]- [9], which makes the tunneling induced broadening a most dominant factor for the linewidth broadening. For this reason, we have included only tunneling induced broadening and neglected all scattering or other physical processes which can cause an uncertainty in the phase of electrons, and assumed 15 K and 2D doping density of 1.6×10^{11} cm^{-2}.

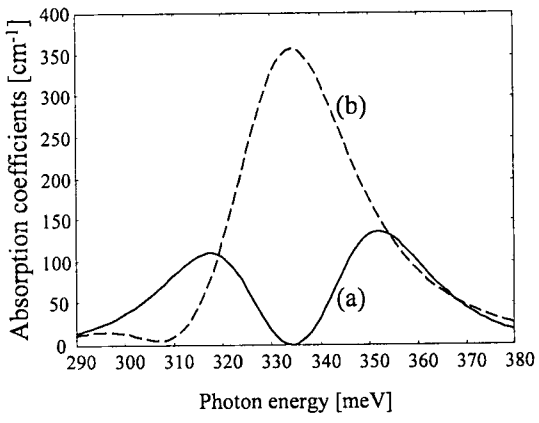

FIG. 3. Calculated absorption coefficients of the structure shown in Fig. 1 (a) without a parallel electric field and (b) with an electric field (E_{t0} = 62 meV and σ_t =15 meV).

Fig. 3 confirms our discussion on the feasibility of peak-to-zero modulation of optical absorption discussed above ((a) absorption cancellation via electrically induced transparency and (b) effectively single absorption peak at the zero absorption wavelength in (a)). We find that the absorption coefficients plotted in Fig. 3 are quite small for the efficient modulation of incident light. For a practical application, they are required to increase by at least ten times, which means we have to increase the background doping density by ten times. However, if we increase the doping concentration, the probability of the electron's scattering also increases, which breaks the coherence of the electron's wavefunction and thus, quantum interferences. Increasing the electron's density avoiding this coherence breaking is a very challenging problem and requires a technical break-through.

In summary, a modulation scheme of optical absorption in a coupled asymmetric QW structure via electrically controllable quantum interference was proposed. We suggested a specific QW structure using this scheme and showed the feasibility with the calculation of wavefunctions and absorption coefficients.

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[19] The effective potential depth of well 1 or 2 can be written as [15]- [17]

$$V_{1(2),eff} = V_{1(2)} + \frac{\hbar^2 k_r^2}{2}\left[\frac{1}{m_{1(2)}} - \frac{1}{m_b}\right], \qquad (1)$$

where k_r denotes the parallel wavevector of electrons which can be controlled practically by an external electric field parallel to the QW plane [15], and m_2, m_2, and m_b are the effective masses of electrons in well 1 and 2, and barrier, respectively. Since $m_2 < m_1$, the effective potential depth of well 2 changes (becomes shallower) more significantly than in well 1. Thus the eigenenergy of $|1_2\rangle$ becomes higher than that of $|0_1\rangle$.