Normal Incident Intersubband Absorptions in EuTe/PbTe Superlattices

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***Abstract*— Normal incident intersubband absorptions were observed in EuTe/PbTe double-well superlattices with two kinds of PbTe quantum wells separated by monolayer EuTe prepared on KCl (100) substrates. The absorption was caused through the modulation of quantum-well potential along superlattice direction: The absorption energy shifted with the variation of PbTe well thickness, and two kinds of absorptions were observed by modulating EuTe barrier thickness. A normal incident intersubband absorption was also observed in a simple EuTe/PbTe short period superlattice. The origin of the absorption is discussed with a fluctuation of barrier-thickness.**

***Index Terms*— intersubband absorption, IV-VI semiconductor, optical property, superlattice**

Intersubband (ISB) transitions in semiconductor quantum wells (QWs) have various applications such as infrared photodetectors, quantum cascade lasers, and ultrafast optical modulators[1-2]. According to the simple selection rule, the transition can be induced only by TM polarized light. However, several studies have been reported on ISB absorptions induced by TE polarized light [3-7]. Three dimensional confinements in quantum dots or impurity states cause absorptions by TE polarized light, and absorption between subbands with different core states is also possible. We recently observed a strong intersubband absorption in EuTe/PbTe double-well superlattices (SLs) [8]. Here, we describe detailed optical properties of the EuTe/PbTe SLs with the discussion of the subband structures.

PbTe is one of the semiconductors studied from early stage of semiconductor research. It crystallizes in rock-salt structure and has a many-valley direct-gap at L-points of Brillouin zone, with a large effective mass anisotropy of m_l/m_t=10. The constant energy surfaces at the conduction-band bottom and valence-band top are similar to the conduction-band bottom of Ge. In IV-VI semiconductors such as PbTe and PbS, s-orbitals of both anion and cation form the bottom of valence band. Core wave functions of the conduction band bottom and valence band top are p-like with odd and even parities, respectively [9]. When the SL is grown along z:[001] direction, band edge effective mass along the SL direction becomes $m_{zz}=3m_tm_l/(m_t+2m_l)$, and E-$\boldsymbol{k}$ relationship along the SL direction is given by

$$E(1+E/E_g)=\hbar^2k_z^2/2m_{zz}. \qquad (1)$$

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Quantum levels of the IV-VI semiconductor SLs have been calculated by envelope function approximation as well as III-V SLs[10]. Considering the envelope function approximation, real wave function in the conduction band $\psi(\boldsymbol{r})$ is given by the product of core wave function $u(\boldsymbol{r})$ and envelope function $F(\boldsymbol{r})$ as $\psi(\boldsymbol{r}) = u(\boldsymbol{r})F(\boldsymbol{r})$. ISB absorption probability is given by Fermi's golden rule, and proportional to the square of the matrix element

$$\langle\psi_2|A\bullet\nabla|\psi_1\rangle=\langle u_2|A\bullet\nabla|u_1\rangle\langle F_2|F_1\rangle, \qquad (2)$$

where $\boldsymbol{A}$ is vector potential. In effective mass approximation, envelope functions in conventional semiconductors with parabolic band become orthogonal because they are eigen-functions of the same Hamiltonian. Thus the matrix element of Eq. (2) becomes zero. If core function varies with energy, E-$\boldsymbol{k}$ relationship shifts from parabolic band, and envelope functions $F_1(\boldsymbol{r})$ and $F_2(\boldsymbol{r})$ become eigenfunctions of different Hamiltonian with different effective masses. Thus matrix element in Eq. (2) can have nonzero value. In narrow direct-gap semiconductors, the E-$\boldsymbol{k}$ relationship near the bottom of conduction band has a large nonparabolicity due to a mixing of core states in valence-band top and conducton-band bottom[9], and ISB absorption is possible when $\langle F_2|F_1\rangle$ has nonzero value.

We prepared n-type EuTe/PbTe SLs with monolayer EuTe barriers by hot wall epitaxy on thick PbTe buffer layer grown on KCl (100) substrate. Band gap of the EuTe is around 2 eV, whereas that of PbTe is 0.32 eV at room temperature (RT). Band edge discontinuity as high as 1 eV is expected in the conduction band[11]. Four kinds of SLs were prepared. Sample A (SL A) is a simple short-period SL with 300 periods of two monolayers EuTe and 6.5nm PbTe (corresponds to 20 monolayers of PbTe) grown on 13.5μm PbTe buffer layer. Sample B (SL B) is double-well SL with 200 periods of monolayer EuTe / 10.3nm PbTe / monolayer EuTe / 3.6nm PbTe grown on 34μm PbTe buffer layer. Sample C is double-well SL with 200 periods of monolayer EuTe / 7.4nm PbTe / monolayer EuTe / 2.9nm PbTe grown on 8.5μm PbTe buffer layer. Sample D has double well structure with 200 periods of two monolayers EuTe / 8.1nm PbTe / monolayer EuTe / 2.9nm PbTe grown on 26μm PbTe buffer layer. Bi dopant was used as donor impurity, and the carrier concentration in the SL layer was estimated as 3×10^{18} cm^{-3} by Hall measurement. Subband structures calculated for the SLs by envelope function approximation are shown in Fig. 1.

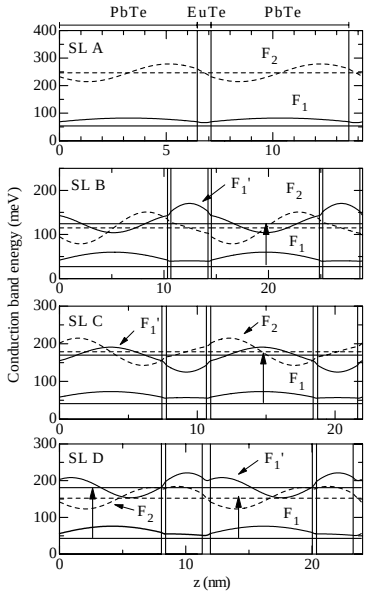

Fig.1 Subband structures of EuTe/PbTe superlattices.

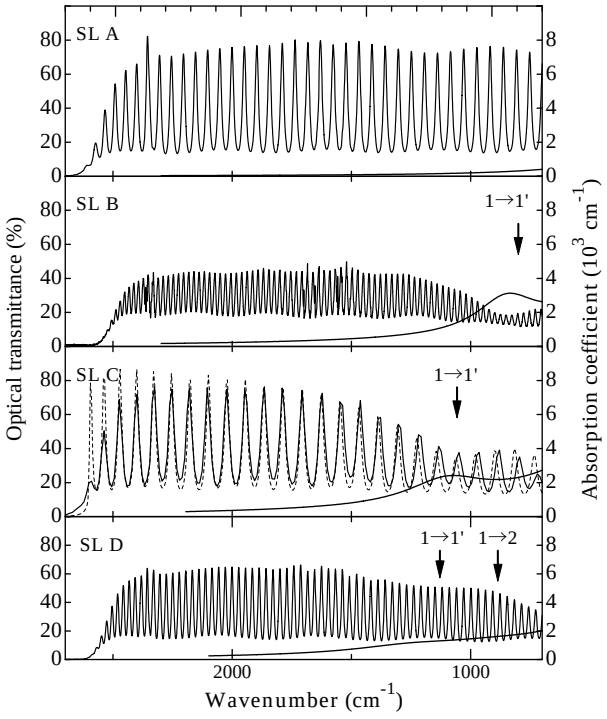

Fig. 2. Optical transmission spectra and absorption coefficients of EuTe/PbTe superlattices at 300K.

Envelope functions are even and odd functions at the center of the PbTe well, and the positions with highest $|F(\boldsymbol{r})|$ are in the wider PbTe well for F_1 and F_2, and in the narrower PbTe for F_1' in samples B and C. In sample D, position with highest $|F(\boldsymbol{r})|$ is shifted from the center of quantum well by the modulation of EuTe barrier thickness.

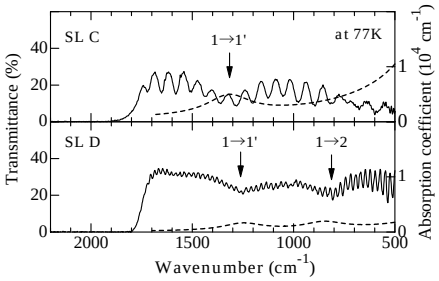

Fig. 3. Optical transmission spectra and absorption coefficients of SLs C and D at 77K.

Room temperature (RT) optical transmission properties were measured by Fourier transform infrared (FTIR) spectrometer for all SLs at normal incidence and the results are shown in Fig. 2 with absorption coefficients obtained by simulation. In the simulation, we assumed Lorentian-shape ISB absorption and free-carrier absorption proportional to the wavelength squared. The simulated spectra are shown by dashed line in the Fig. 2 for SL C. In the SL A, envelope functions $F_1(\boldsymbol{r})$ and $F_2(\boldsymbol{r})$ are orthogonal because they are even and odd functions at the center of the QW, respectively. Thus no ISB absorption at normal incidence occurred. On the other hand, strong ISB absorptions were observed in samples B and C with absorption coefficients as high as 2000 cm^{-1}. The absorption corresponds to the transition between F_1 and F_1' shown in Fig. 1. In this case, envelope functions $F_1(\boldsymbol{r})$ and $F_1'(\boldsymbol{r})$ are both even functions at the center of wider QW. Theoretical absorption positions are also indicated by arrows in Fig. 2. In sample D, broad and relatively weak absorption was observed due to two kinds of absorption indicated in Fig. 1. Figure 3 shows the optical transmission spectra at 77K for SLs C and D. The absorption became clear at 77K, and clear two kinds of absorptions were observed in sample D. A strong ISB absorption was observed at normal incidence also in a simple short-period SL similar to sample A, resulting from a modulation of periodic potential due to the fluctuation of EuTe barrier thickness.

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