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Coherent oscillations of holes in $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ surface quantum well

SALAHUDDIN KHAN[1,*], J JAYABALAN[1], ASHA SINGH[1], RAMA CHARI[1], SUPARNA PAL[2], S PORWAL[2], T K SHARMA[2] and S M OAK[2]

[1]Laser Physics Applications Section, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India
[2]Semiconductor Laser Section, Raja Ramanna Centre for Advanced Technology, Indore 452 013, India
*Corresponding author. E-mail: skhan@rrcat.gov.in

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Abstract. We show that in a $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ near-surface quantum well, there is coherent oscillation of holes observed in time-resolved reflectivity signal when the top barrier of the quantum well is sufficiently thin. The quantum well states interact with the surface states under the influence of the surface electric field. The time period of the observed oscillation is 120±10 fs.

Keywords. Pump–probe reflectivity; near-surface quantum well; ultrafast spectroscopy.

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1. Introduction

The phenomenon of quantum beats originates from the interference arising from two transitions sharing a common ground or excited states [1]. In semiconductor quantum wells, such a situation can occur when carriers are generated due to excitation by a short laser pulse having a spectrum wider than the difference in two transition energies [2]. Coherent beating has been observed in asymmetric double quantum wells and multiple quantum wells [3,4]. Very recently, charge oscillations between heavy and light-hole sub-bands in the plane of a (1 1 0)-oriented GaAs QW sample have been reported [5]. In this work we report a similar phenomenon in a $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ near-surface quantum well. $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ quantum well (QW) structures are widely used as emitters and modulators [6–8]; however there is not much information available about their ultrafast carrier dynamics. We show that if the top barrier layer is sufficiently thin, the quantum well states can couple with surface states located near the band edges leading to ultrafast oscillations in the induced change in reflectivity.

2. Experimental details

Standard degenerate pump–probe reflectivity geometry is used with a 90 fs, 82 MHz titanium:sapphire laser [9,10]. The pump and probe beam polarizations were kept orthogonal. The probe delay is varied using an optical delay based on a microstepper motor. The change in the probe reflectivity is monitored using a photodiode lock-in amplifier combination. Single quantum wells (SQW) of $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ were grown by metalorganic vapour phase epitaxy (MOVPE) on a [0 0 1] n^+-doped GaAs substrate. The schematic layer structure of the samples is shown in figure 1. The two quantum well samples used in this work were of similar structure differing only in the top $Al_{0.7}Ga_{0.3}As$ barrier thickness. For sample QW5 this was 5 nm whereas for sample QW50 it was 50 nm. In the QW5 sample a strong interaction is expected between the quantum well states and surface states. This is supported by the observation that no CW photoluminescence (PL) could be observed in QW5 at room-temperature. The room-temperature CW PL spectrum of QW50 is shown in figure 2. The three transitions are assigned as *e1-lh1*=1.565 eV (792 nm), *e1-hh1*=1.579 eV (785 nm) and *e1-hh2*=1.6 eV (775 nm) after deconvoluting the PL spectrum. The transition, *e1-hh1*, is the strongest one. In the transient reflectivity measurements the wavelength of the femtosecond laser was kept at 786 nm which is near the *e1-hh1* transition as shown in figure 2. All the measurements were done at room temperature.

3. Coherent oscillations

As shown in figure 2, the femtosecond laser has a wide spectrum with a FWHM value of ∼15 nm. Therefore, when the peak wavelength of laser is at 786 nm, all the three energy levels are excited simultaneously. Figures 3 and 4 show the recorded transient reflectivity

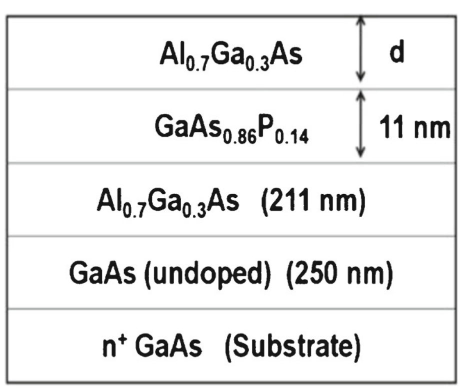

Figure 1. QW sample layer structure. For sample QW5 d=5 nm and for QW50 d=50 nm

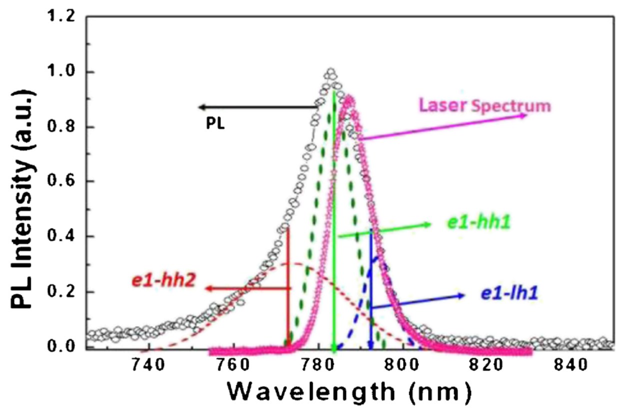

Figure 2. Room-temperature cw PL spectrum of QW50 sample along with the femtosecond laser spectrum.

of the two QW samples in the sub-ps region. The transient reflectivity signal in both the quantum wells showed an initial rise which followed the pump pulse. The decay could be fit to a double exponential indicating that there is a fast and a slow component to this part of the decay. In QW5 the slower component clearly has a dependence on pump power. The fast component is extracted by subtracting the exponential fit to the slower decay. The extracted fast decay is shown in figures 5 and 6 for QW50 and QW5 respectively.

In QW5, clear oscillations are seen in the tail end of the decay curve. Such oscillations have been reported in differential transmission of an asymmetric double quantum well with a thin barrier when an electric field is applied across it [3]. The carriers tunnel under the influence of the applied electric field, and oscillate coherently between the two quantum wells thus creating an oscillating dipole. This oscillation leads to quantum beats in differential transmission and four wave-mixing signals [3]. In QW5 the surface states and quantum well states together can form a double quantum well structure. The observed

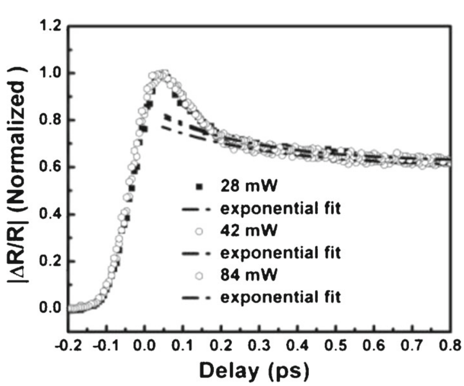

Figure 3. Transient reflectivity signal from QW50 for different pump powers, fit to an exponential decay for the latter part of the signal.

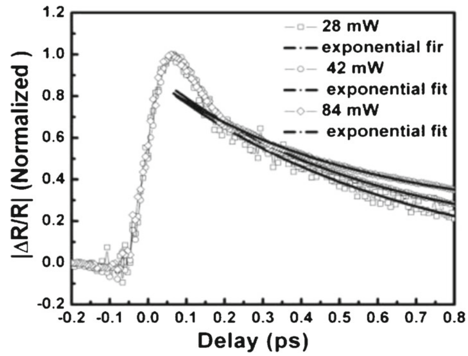

Figure 4. Transient reflectivity signal from QW5 for different pump powers, fit to an exponential decay for the latter part of the signal.

oscillation in the transient reflectivity can occur if the states in the two quantum wells get coupled due to tunnelling. In the present case, the surface electric field is given by

$$E_{\text{surface}} = V_{\text{in-built}}/W_{\text{depletion-width,}} \tag{1}$$

where $V_{\text{in-built}} = 0.7$ eV [11] and $W_{\text{depletion-width}}$ is given by [11]

$$\text{W}_{\text{depletion-width}} = \sqrt{\frac{2\varepsilon \text{V}_{\text{in-built}}}{q^{*}N_{\text{D}}}}, \tag{2}$$

where q is the electronic charge and N_{D} is the doping density. This will give an electric field of about ∼3–4 kV/cm penetrating into the quantum well. When a femtosecond pump pulse is incident on the sample, *e*–*h* pairs are generated in the quantum well. Under the influence of the electric field the holes move towards the surface states. The period of oscillation for any two superposed states is given by

$$\Delta E = h\upsilon_{\text{oscillations}} = h^{*}(1/T_{\text{oscillations}}), \tag{3}$$

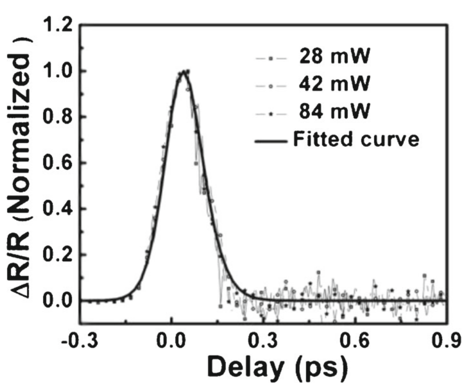

Figure 5. Transient reflectivity signal from QW50 for different pump powers after the removal of slower part.

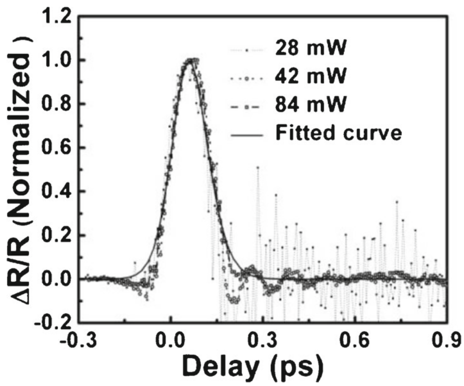

Figure 6. Transient reflectivity from QW5 for different pump powers after the removal of slower part.

where ΔE is the energy difference of two energy states in the two quantum wells, h is Planck's constant and $\upsilon_{\text{oscillations}}$ is the frequency of coherent oscillations. The period of oscillation observed in our measurement is 120 fs $\pm$ 10 fs. This corresponds to an energy level separation of 33 meV. This model is consistent with the observation that no oscillations were observed in QW 50. In this case, the interaction with surface states is much less due to the 50 nm thick barrier and the interaction between the two quantum wells would be much less.

4. Conclusion

We have observed sub-ps oscillations in the transient reflectivity of $GaAs_{0.86}P_{0.14}/Al_{0.7}Ga_{0.3}As$ near-surface quantum well. To the best of our knowledge, this is the first observation of such a phenomenon in surface quantum wells. We have shown that a coherent beating can occur when the top barrier layer of the quantum well is sufficiently thin. We attribute this behaviour to the interaction of quantum well states with the surface states. This interaction arises from the tunnelling of photogenerated holes towards the surface due to the presence of electric field. The time period of observed oscillation is 120 $\pm$ 10 fs. This leads to a possibility of using such structures to generate THz transient [12].

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