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Investigation of optical response in type-II InAs/AlSb nano-scale heterostructure: A novel dual structure*

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Abstract

This paper reports the optical properties of type-II InAs/AlSb novel dual nano-scale heterostructure. The duality of the heterostructure has been investigated by different types of doping introduced into the barrier region of the heterostructure. On doping of amount 1.5 x $10^{15}/cm^3$ in barriers, it has been observed that the type-II InAs/AlSb heterostructure can work as a quantum well infra-red photodetector (QWIP) as well as like a diode laser working in mid-infra red (MIR) region. In case of diode laser, the optical gain as well as lasing wavelength both has been found to shift by varying the doping concentration. The maximum optical gain within TM mode has been found ~ 800/cm, and within TE mode, it is ~ 2800 /cm. Due to its dual nature, the type-II InAs/AlSb nano-scale heterostructure is claimed as a novel structure and very suitable for optoelectronic applications.

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Keywords: Type-II heterostrcuture, InAs, AlSb, Optical Gain

1. Introduction

In last decade, III-V semiconductors based type-II quantum well heterostructures have been extensively investigated for the operation in infra red regions. Recently, H. K. Nirmal et al. [1] have studied type-II InGaAs/GaAsSb nano-

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-scale heterostructure and a very high optical gain have been reported in the structure in comparison to other heterostructures. In reference [2] it has been shown that of optical gain in type-II InGaAs/GaAsSb heterostructure can be tuned under high pressure. Therefore, such types of heterostructures have attracted a great attention of researchers towards their potential applications in the area of optoelectronic devices operating in short wave infra-red (SWIR) and mid wave infra-red (MWIR) wavelength regions. InGaAs/GaAsSb 'W'-shaped lasers fabricated on InP substrate operating in SWIR region with low threshold current has been presented in reference [3]. "M"-shaped GaAsSb/InGaAs QW lasers fabricated on InP substrate operating in MIR (mid infra red) region have been presented by Chia-Hao Chang et al. [4]. InGaAs/GaAsSb "W" type quantum well lasing heterostructures for MIR laser applications has been presented in reference [5].

The purpose of the work presented in this paper is to show that the well known simple type-II InAs/AlSb nano-scale heterostructure can work either as QWIP or as lasing nano-heterostructure (diode laser) depending upon nature of the dopants introduced into barrier region of the heterostructure.

2. Structure and theory

The type-II InAs/AlSb structure consists of a single QW of InAs layer (thickness ~ 10 nm) which is sandwiched between the barriers (from both sides) of the AlSb layers (thickness ~ 21 nm). The complete structure is assumed to be fabricated on the substrate InAs pseudomorphically. An important and very interesting feature of this structure is that the spatial separation between electron (in conduction band of the QW) and hole (of barrier region) is very small and hence leads to negligible interband dipole matrix elements. Due to this feature the type-II InAs/AlSb heterostructure neither can be used as a photodetector nor as a gain structure. But, in this work it has been tried to induce the prominent interband dipole matrix elements with the help of doping process and hence existing of optical gain.

Next, in order to investigate the behaviour of the structure, two structures were modelled with different types of doping in barrier regions. In one structure, the barriers were doped with n-type dopants while in second one the dopants were of p-type. In order to study the optical response of both the heterostructures, the wave functions associated with conduction electrons and corresponding the discrete energy levels within the conduction band were calculated. For this calculation, the Schrodinger equation were solved by assuming the semi-parabolic nature of conduction band and as well as effective-mass approximation taking into account. For calculation of wave functions associated with the valence band holes and their discrete energy levels, the eight band **k.p** model was utilized.

In case, if the heterostructure works as a photodetector, then the absorption coefficient can be given as [6];

$$\alpha(\omega) = \frac{4\pi^2 e^2}{n_r c m_o^2 V\omega} \sum_K \left|\hat{e}.p_{ba}\right|^2 \delta(E_b - E_a + \hbar\omega)(f_a - f_b)$$

where n_r is the refractive coefficient , c is speed of light in vacuum.

In case of the quantum well lasing heterostructure or diode laser, the optical gain within transverse electric (TE) and transverse magnetic (TM) modes can be calculated by using Fermi's golden rule and it can be given as [6, 7];

$$G(\hbar\omega) = \frac{2.\pi e^2}{nc\epsilon\omega L m^2} \sum_{\sigma=U,L} \sum_{n,m} \int \left|\left(\hat{e}.\ M_{nm}^{\eta\sigma}(k_t)\right)\right|^2 \times \frac{\left(f_n^c(k_t) - f_{\sigma m}^v(k_t)\right)\left(\frac{\gamma}{\pi}\right)}{\left(E_{\eta,\sigma nm}^{c,v}(k_t) - \omega\hbar\right)^2 + \gamma^2} \frac{k_t dk_t}{2\pi}$$

where L is quatum well width, and f_n^c and $f_{\sigma m}^v$ are the quasi Fermi levels related to conduction and valence bands respectively. In above expression the quantity $M_{nm}^{\eta\sigma}(k_t)$ is momentum matrix element and the term $E_{\eta,\sigma nm}^{c,v}(k_t)$ represents the energy gap between the conduction (*n*) and valence sub-bands (*m*). The symbol $\hat{e}$ represents the direction of electric field and γ represents the half linewidth of the Lorentzian function. The factor of 2 in the above expression accounts for the sum over σ of the hole spins in the valence band only.

3. Results and explanation

To know the optical response of the structure, two heterostructures of InAs/AlSb were modelled with different types (i.e. n- and p- types) of doping in barrier regions. The physics of impurities in type-II InAs/AlSb superlattices has already been reviewed, with emphasis on changes of doping character [8]. In this reference, it has been shown how some impurities can change their doping characters from "deep acceptors" (semi-insulating) to shallow donors (n-type) as functions of layer thicknesses in superlattices such as InAs/AlSb. For first model of InAs/AlSb nano-scale heterostructure, in which the n-type dopants were introduced, the absorption coefficient is simulated and plotted in Fig. 1. From Fig. 1, it is clear that the n-AlSb/InAs/n-AlSb quantum well heterostructure can works as a quantum well infra red photo detector (QWIP). On observing the energy band diagrams (which is not shown here) along with associated wavefunction, it is found that electrons are totally occupied with conduction band of quantum well of InAs material while the holes are with the barriers of AlSb material. Hence during absorption process, the transition will occur between conduction band electrons of InAs quantum well and valence band holes of AlSb barriers. Moreover, the maximum absorption achieved in the heterostructure is ~ 21000/cm, which confirms that such heterostructures with n-type doping in barrier region are good photodetectors. Here it is noted that the type-II InAs/AlSb heterostructure with undoped barriers can neither work as a lasing structure nor as a photodetector.

For another model of InAs/AlSb nano-scale heterostructure, in which the p-type dopants were introduced, the optical gain coefficient is simulated and plotted in figures 2 and 3. In Fig. 2, the optical gain coefficient for the heterostructure of p-AlSb/InAs/p-AlSb within TM mode is plotted. In Fig. 3, the optical gain within TE mode is plotted. From figure 2, it is clear that for undoped barrier regions the TM optical gain is almost negligible because of negligible momentum matrix elements at the zone centre. This gain increases with increasing doping concentration. The maximum optical gain in is found around 800 /cm with in MIR region at doping concentration of 1.5 x 10^{18} /cm^3. This TM optical gain is supposed to be very high in comparison to the TM optical gain existing in the other heterostructures studied so far. The TE optical gain for undoped and doped InAs/AlSb nano-scale heterostructure is illustrated in figure 3. From this figure 3, it is obvious that the TE gain is almost negligible for undoped and as well as for doping concentration of 0.5 x 10^{18} /cm^3.

Again, the TE gain is also found to increase with increasing doping concentration. The peak optical gain within TE mode for the InAs/AlSb is found around 2800 /cm with in MIR region at doping concentration of 1.5 x 10^{18} /cm^3. Recently, such magnitude of TE gain is found to be equivalent to TM gain in a ternary heterostructure of type-I AlGaAs/GaAsP [9]. During achieving the optical gain, the transition will occur between conduction band electrons and valence band holes of InAs quantum well which is the different case as occurs in detection process. It is well known that in type–II InAs/AlSb quantum wells the spatial separation of electrons and holes leads to weak interband dipole matrix elements, except for very narrow InAs layers of a few monolayers. Due to this fact the heterostructure InAs/AlSb is used as interband gain material. Most of the research literature on this material system has focused on inter-sub-band transitions and the device applications in mid infra-red and THz wavelength regions [10].

4. Conclusion

The eight band **k.p** model has been utilized to get the wavefunctions associated with electrons and holes in conduction and valence sub-band, respectively, of the type-II InAs/AlSb nano-scale heterostructure. With the help of these calculations, the type-II InAs/AlSb heterostructure has been modeled with the introduction of n- and p-type dopants into the barrier regions and the dual nature of the heterostructure has been confirmed. With n-type doping, it has been observed that the type-II InAs/AlSb heterostructure can work as a QWIP and with p-type doping it acts as a diode laser working MIR region. In case of diode laser, the optical gain as well as lasing wavelength both has been found to shift by varying the doping concentration. The maximum optical gain within TM mode has been found ~ 800/cm, and within TE mode, it is ~ 2800 /cm. Due to its dual nature, the type-II InAs/AlSb nano-scale heterostructure is claimed as a novel structure and very suitable for optoelectronic applications.

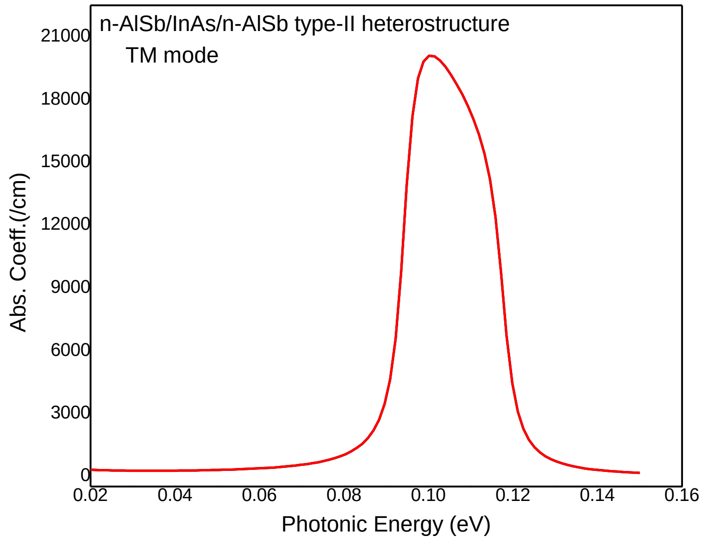

Fig. 1. Behaviour of absorption coefficient in n-AlSb/InAs/n-AlSb type-II nano-scale heterostructure.

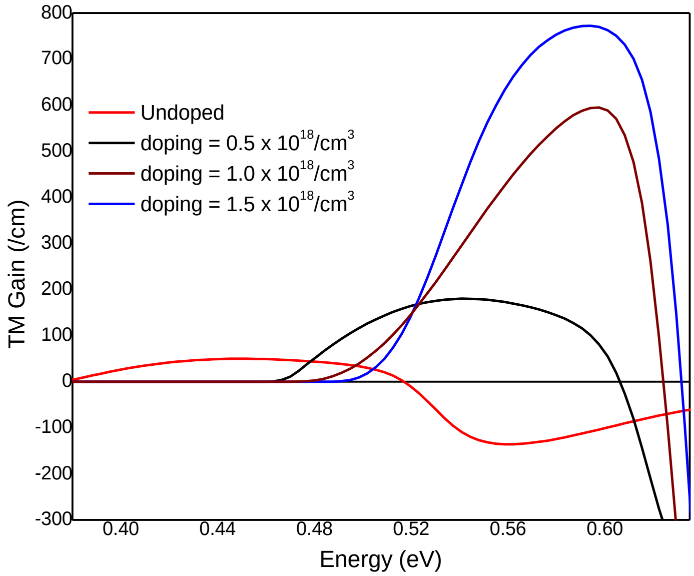

Fig. 2. TM optical gain in type-II p-AlSb/InAs/p-AlSb nano-scale heterostructure.

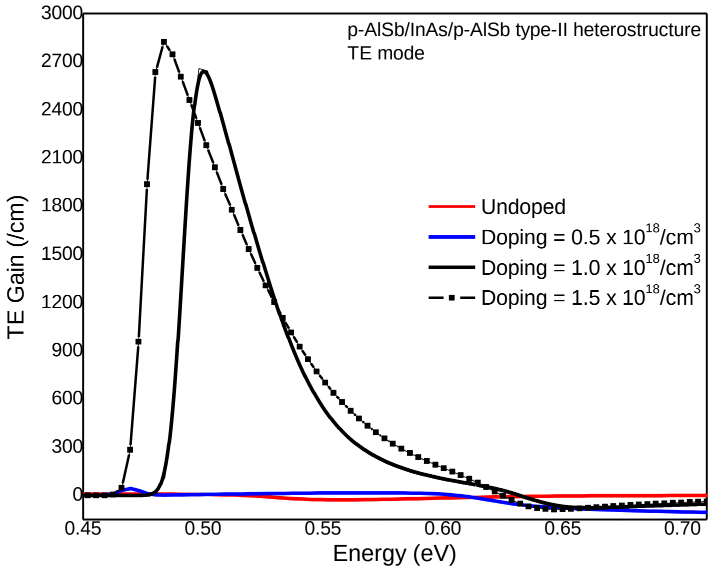

Fig. 3. TE optical gain in type-II p-AlSb/InAs/p-AlSb nano-scale heterostructure.

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