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Enhancement of multisubband electron mobility in asymmetrically doped coupled double quantum well structure

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ABSTRACT

We study the effect of coupling of subband wave functions on the multisubband electron mobility in a barrier delta doped GaAs/$Al_xGa_{1-x}As$ asymmetric double quantum well structure. We use selfconsistent solution of the coupled Schrödinger equation and Poisson's equation to calculate the subband wave functions and energy levels. The low temperature mobility is considered by using scatterings due to ionized impurities, interface roughness and alloy disorder. We show that variation of the width of the central barrier considerably affect the interplay of different scattering mechanisms on electron mobility through intersubband effects. Under single subband occupancy, the mobility increases with decrease in the barrier width as functions of doping concentration as well as function of well width. However, in case of double subband occupancy, effect of intersubband interaction yields opposite trend, *i.e.*, increase in mobility with increase in barrier width. It is gratifying to show that in case of asymmetric variation of well widths the mobility shows nonmonotonic behavior which varies with change in the width of the central barrier under double subband occupancy.

1. Introduction

In recent years, a great deal of attempts has been made to study asymmetric quantum well structures because of their potential applications in electronic and optical devices [1–10]. Efforts have been made to utilize asymmetrically doped coupled quantum well GaAs/AlGaAs structures to develop and characterize tunable mid-infrared photodetectors [1]. Suitably engineered GaAs/AlGaAs double quantum well structures have been shown to exhibit coherent terahertz emission due to intersubband excitation between two lowest conduction subbands [2]. InGaN based light emitting devices with asymmetric coupled quantum wells yield improved light emission intensity compared to that of a symmetric coupled quantum well device [3]. Attempts have been made to study the magnetic-field-induced charged excitonic transitions in modulation-doped AlGaAs/GaAs asymmetric coupled double quantum wells [4]. Recently it has been shown that in an asymmetric double InGaAs quantum well structure the coherent excitonic interwell coupling originates from many-body effects [5]. Further it has been shown that in a coupled asymmetric quantum well system the eigenstate probability distribution localizes exclusively either in the wide or the narrow parts of the well pair [6]. Attempts have also been made to investigate electron spin dynamics by the time-resolved Kerr rotation technique in a pair of special GaAs/AlGaAs asymmetric quantum well samples to explore the possibility of developing spin based electronic devices [7]. A direct determination of nonradiative lifetimes in Si/SiGe asymmetric quantum well structures shows that the barrier and well widths play an important role in the determination of the carrier life time. Further by comparing with experimental and theoretical data obtained for mid-infrared GaAs/$Al_xGa_{1-x}As$ quantum well systems, it has been shown that interface roughness scattering plays a dominant role for a wide range of semiconductors at low temperature [8]. Attempts have also been made to study electron transport in asymmetric quantum well structures by considering lowest subband occupancy [9,10]. However, in a quantum well system, where more than one subband is occupied, the intersubband interaction plays a vital role on the subband mobility [11–15]. Intersubband effects create additional intersubband scattering rates and also modify the intrasubband scattering rate through the dielectric screening of the scattering potentials [11–15].

In the present paper we study multisubband electron mobility of a coupled asymmetric double quantum well structure. Variation of the central barrier width (b) changes the coupling of the subband wave functions of individual wells thereby changing the subband energy levels and wave functions which in turn affect the occupation of subbands of the coupled structure. As a result the strength of the scattering potentials also amended leading to change in the mobility. We consider GaAs/AlGaAs double quantum well in which the asymmetry of the structure is employed by

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introducing delta doped layer in one of the side barriers only and also taking different well widths. We obtain the subband electron energy levels and wave functions for the coupled structure by adopting selfconsistent solution of the Schrodinger equation and Poisson's equation. We calculate the low temperature electron mobility μ by considering ionized impurity (*imp*-), interface roughness (*ir*-) and alloy disorder (*al*-) scatterings. We adopt static dielectric response function formalism to calculate the screened scattering potentials by using the random phase approximation (*RPA*) [11–15].

We show that μ increases with increase in the doping concentration (*Nd*). The mobility is mostly governed by *imp*- and *ir*-scatterings. The effect of *ir*-scattering, which is more dominating at low values of *Nd*, decreases with increase in *Nd* so that the effect of *imp*-scattering on mobility enhances. The doping dependence of μ for different *b* also shows interesting results. As long as single subband is occupied, the mobility decreases with increase in *b*. A deviation in the trend occurs for small *b* at small *Nd* due to strong influence of *ir*-scattering. However, once double subband is occupied, the trend is reversed. The drop in mobility at the onset of occupation of the second subband and also the doping concentration at which the drop occurs, decrease with increase in *b*. The effect of *b* on the well width dependence of mobility also shows interesting results. The increasing trend in μ with increase in well width slowly reverses as the barrier width increases due to gradual dominance of the intrasubband scattering rate matrix element of the higher occupied subband. We show that the mobility can be enhanced considerably at small well widths having double subband occupancy by increasing the barrier width. We further show that by increasing well width, the occupation of subbands goes on changing *viz.*, from single subband to double subband and then again single subband occupancy. Accordingly the mobility shows a drop and then a rise near the change in occupancy of subbands. Our analysis therefore will help in choosing suitable structure parameters so that the mobility becomes a maximum. Our results of mobility of a single side barrier delta doped asymmetric double quantum well structure can be utilized for low temperature device applications.

2. Theory

We consider a GaAs/$Al_xGa_{1-x}As$ double quantum well structure in which the left barrier is delta doped with a layer of Si of width *d* and doping concentrations *Nd* at a spacer distance *s* from the nearest interface (Fig. 1). The wells, of widths *w*1 and *w*2, are separated by a thin barrier of width *b*. Diffusion of electrons cause band bending due to Coulomb interaction with the ionized donors in the barrier. The concentration distribution of impurities and electrons $n_D(z)$.

and $n(z)$ along the growth axis, *viz.*, *z*-axis can be written as:

$$n_D(z) = \begin{cases} Nd & -(d+s+w1+b/2) < z < -(s+w1+b/2) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

$$n(z) = \sum_n n_n \left|\psi_n(z)\right|^2 \qquad -\infty < z < +\infty \quad (2)$$

$\psi_n(z)$ are the subband wave functions and summation *n* is over the subband levels. n_n is the number of electrons per unit area in the *n*th subband which can be written as [11]:

$$n_n = \left(mk_B T/\left(\pi\hbar^2\right)\right)\ln\left[1+\exp(E_F-E_n)/k_BT\right] \quad (3)$$

E_n are the subband energy levels and E_F is the Fermi energy. At temperature $T=0$ K, the surface electron density N_s and the Fermi energy can be related as [11]:

$$N_s = m/\left(\pi\hbar^2\right)\sum_{n=1}^{N}(E_F-E_n)\ \theta\ (E_F-E_n) \quad (4)$$

N is the number of filled levels, θ is the Heaviside step function.

We obtain the subband energy levels E_n and wave functions $\psi_n(z)$ by adopting selfconsistent solution of the one dimensional Schrödinger equation and the Poisson's equation. In Fig. 1, we present a schematic diagram of the potential profile, subband energy levels and wave functions of the single side doped asymmetric double quantum well structure. Since at $T=0$ K, the electrons on the Fermi surface take part in the conduction process, the subband transport life time can be expressed as $\tau_n=\tau_n(E_{Fn})$. Here $E_{Fn}=E_F-E_n$ is the Fermi energy of *n*th subband. The relaxation time τ_n for a multisubband occupied system can be derived from the Boltzmann transport equation containing the intrasubband and intersubband scattering rate matrix elements in a mixed way [11–14]. For the lowest occupied subband ($n=0$), one can write τ_0 in terms of intrasubband scattering rate matrix element b_{00} as [14]:

$$\frac{1}{\tau_0} = b_{00} \quad (5)$$

Similarly, for a double subband is occupied structure ($n=0, 1$), both τ_0 and τ_1 contain intrasubband and intersubband scattering rate matrix elements (c_{01} and d_{01}) as shown below [14]:

$$\frac{1}{\tau_0} = \frac{(b_{00}+c_{01})\ (b_{11}+c_{10})-d_{01}d_{10}}{(b_{11}+c_{10})+\ (E_{F1}/E_{F0})^{1/2}\ d_{01}}$$

$$\frac{1}{\tau_1} = \frac{(b_{00}+c_{01})\ (b_{11}+c_{10})-d_{01}d_{10}}{(b_{00}+c_{01})+\ (E_{F0}/E_{F1})^{1/2}\ d_{10}} \quad (6)$$

The scattering rate matrix elements b_{nn}, c_{nm} and d_{nm} can be expressed in terms of scattering potential matrix elements $V_{nm}^{eff}(q)$ as [14]:

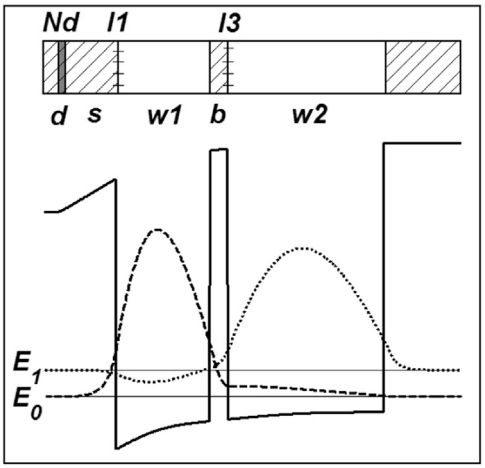

Fig. 1. Schematic diagram of the one side barrier doped asymmetric double quantum well structure along with the potential energy profile, subband energy levels and wave functions.