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Millimeter and Sub-millimeter wave Response of Two-Dimensional Hot Electrons in double delta doped GaAs Quantum Well

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Abstract—**Millimeter and sub-millimeter wave response of two-dimensional hot electrons in double delta doped GaAs quantum well is studied here incorporating deformation potential acoustic, polar optic, ionized background and remote impurity scatterings in the framework of heated drifted Fermi-Dirac distribution function. The inclusion of delta doping is found to enhance the two-dimensional electron density which in turn improves the ac mobility in the GaAs quantum wells thereby providing scope of getting higher speed devices in future.**

Index Terms— **Quantum wells, delta doping, carrier scattering, polar optical phonon, coulomb interaction, sheet density.**

I. INTRODUCTION

Recent advances in crystal growth techniques have made possible the fabrication of quasi-low-dimensional structures such as quantum wells (QWs). The possibility of realization of high speed nano-devices using such structures has stimulated active research in quasi-low-dimensional structures.

In quantum well (QW), the density-of-states and scattering rates of the carriers are different from those of bulk semiconductors. In such structures, mobility of the two-dimensional electron gas is enhanced considerably at low temperature because of modulation doping technique [1]. The carrier mobility in quantum wells can further be enhanced by placing an undoped spacer layer between the doped barrier and undoped channel layer [2]. The spacer layer increases the separation between the carriers and ionized donors thereby increasing the electron mobility because of less Coulomb interaction [3, 4].

Due to structural limitations the maximum carrier density that can be obtained in conventional homogeneously doped QW is limited. This carrier density limit in QW can be surpassed in delta doped heterostructures [5]. When a semiconductor is delta doped, the ionized donor atoms create a continuously positive sheet of charge which bends the conduction band to form a V-shaped potential well [6]. The delta doped quantum wells have the following advantages. The first advantage arises from those of the delta-doping technique, including higher mobility, greater electron density and uniform electron distribution [7]. The second advantage is the reduction of size of the quantum wells [7]. Since the spatial distribution of dopants is well controlled and confined to a single atomic layer, the size of the quantum well is reduced. It has been reported that the sheet density in delta doped structures is nearly doubled with respect to the densities obtained in modulation doped heterostructures [8, 9].

In the present work, we investigate the two dimensional electron densities confined in the quantum wells in delta doped GaAs/AlGaAs quantum well structures. We also investigate the ac mobility values in the delta doped GaAs quantum well in the framework of a heated drifted Fermi-Dirac distribution function and compared them with conventional homogeneously doped GaAs QW. The carrier scattering by longitudinal optic phonon, deformation potential acoustic phonons, remote and background-ionized impurities are incorporated in the present calculations.

II. THEORY

Let us consider a GaAs/AlGaAs square QW of infinite barrier height. The AlGaAs barriers are symmetrically delta-doped at a distance Ls from the heterojunction interface. A schematic diagram and a simplified energy band diagram of the double delta doped quantum well are shown in Figs. 1 and 2. The 2D carrier concentration, QW width and other parameters used here are such that there is only one subband in the well and the carriers populate only the lowest subband. The zero order approximation for the electronic wave function and potential in the QW are given by [10].

$$\psi_o(z) = (2/L_Z)^{1/2} Cos\left(\frac{\pi z}{L_Z}\right) \tag{1}$$

and

$$V_o(z) = -\frac{e^2 N_S}{k_1 L_Z}\left\{\left[1-\cos\left[\frac{2\pi z}{L_Z}\right]\right]\frac{L_z^2}{4\pi^2}+\frac{z^2}{2}\right\} \tag{2}$$

The energy balance equation of the QW can be written as

$$\Delta\varepsilon_c = V_H + V_C + \varepsilon_2 + V_S - \varepsilon_0^1 - \left(\varepsilon_F - \varepsilon_0^1\right) \tag{3}$$

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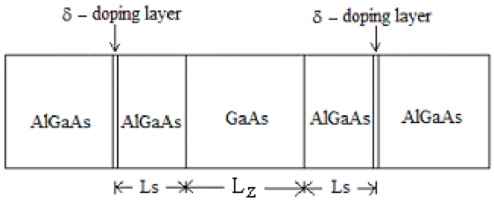

Figure 1. A schematic diagram of a delta doped GaAs/AlGaAs Quantum well.

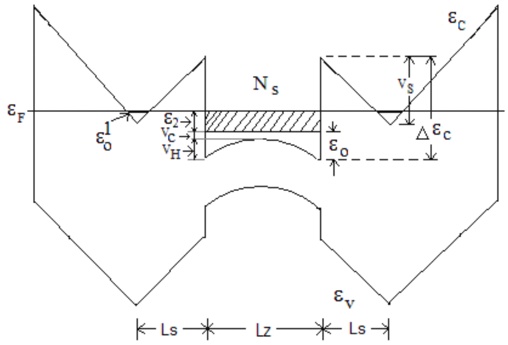

Figure 2. A simplified Energy band diagram of a delta doped GaAs/AlGaAs Quantum well.

Assuming $\left(\varepsilon_F - \varepsilon_0^1\right) = 0$, (3) reduces to

$$\Delta\varepsilon_c = V_H + V_C + \varepsilon_2 + V_S - \varepsilon_0^1 \tag{4}$$

The value of V_c from the first-order perturbation theory is

$$V_C = \frac{h^2}{8m^* L_Z^2} - \frac{e^2 N_S L_Z}{24k_1}\left(1 - \frac{3}{\pi^2}\right) \tag{5}$$

The remaining terms of (4) are given as [10, 11]

$$V_H = \frac{e^2 N_S L_Z}{8k_1}\left(1 + \frac{4}{\pi^2}\right) \tag{6}$$

$$\varepsilon_2 = \frac{\pi h^2}{m^*} N_S \tag{7}$$

$$V_S = \frac{e^2 N_S}{2k_2} L_Z \tag{8}$$

$$\varepsilon_n^1 = 2^{-7/3}(n+1)^{2/3}\left(e^2 2\pi h n^{2D} / k_2\sqrt{m^*}\right)^{2/3} \tag{9}$$

$$\Delta\varepsilon_c = 0.66\Delta\varepsilon_g \tag{10}$$

In the above expressions k$_1$ and k$_2$ are the dielectric constants in GaAs and AlGaAs, respectively, K_B is Boltzmann's constant, $\Delta\varepsilon_g$ is change in band gap, N_S is the carrier concentration in the well and n^{2D} is the donor density.

Inserting the above values in (4), we derived the expression for 2D electron density in the delta doped QW which is given as

$$N_S = \frac{\left(\Delta\varepsilon_C - \frac{h^2}{8m^* L_Z^2} + 2^{-7/3}\left(e^2 h n^{2D} / k_1\sqrt{m^*}\right)^{2/3}\right)}{\left(\frac{e^2 L_Z}{8k_1}\left(1 + \frac{4}{\pi^2}\right) - \frac{e^2 L_Z}{24k_1}\left(1 - \frac{3}{\pi^2}\right) + \frac{\pi h^2}{m^*} + \frac{e^2}{2k_2} L_s\right)} \tag{11}$$

The 2D electron density for the homogeneously doped QW is derived using the procedure adopted in [10].

Reduced ionized impurity scattering and improved carrier concentration in the QW establish a strong electron-electron interaction. A heated drifted Fermi-Dirac distribution function for the carriers characterized by an electron temperature T_e, and a drifted crystal momentum p_d [12] is hence assumed for the carriers. In the presence of an electric field F applied parallel to the heterojunction interface, the carrier distribution function $f(\vec{k})$ is expressed as,

$$f\left(\vec{k}\right) = f_o(E) + \frac{\hbar \vec{p}_d \vec{k}}{m^*}\left(-\frac{\partial f_o}{\partial E}\right)\cos\gamma \tag{12}$$

where, $\vec{k}$ is the two-dimensional wave vector associated with the kinetic energy E, m***** is the electronic effective mass and γ is the angle between the applied electric field $\vec{F}$ and the two dimensional wave vector $\vec{k}$, $f_o(E)$ is the Fermi-Dirac distribution function for the carriers, $\vec{p}_d$ is the drift crystal momentum and ħ is Planck's constant divided by 2π. Expressions for dc and ac mobility are derived from energy and momentum conservation equations of electrons following the procedure adopted in [12] and are given by $\mu_{dc} = \frac{p_o}{m^* F_o}$ and $\mu_{ac} = \frac{\sqrt{p_{1r}^2 + p_{1i}^2}}{m^* F_1}$. The phase lag θ of the resulting alternating current behind the applied field is expressed as $\phi = \tan^{-1}\left(-p_{li}/p_{lr}\right)$

III. RESULTS AND DICCUSSION

Numerical calculations are performed for delta doped GaAs/Al$_x$Ga$_{1-x}$As with the parameters give in [14]. The variation of 2D electron density N$_s$ with quantum well width L$_Z$ for different values of L$_S$ for a doping density of $1\text{x}10^{16}$ m^{-2} is shown in Fig. 3. The 2D electron density increases with increasing L$_Z$ and with decreasing L$_S$. Since larger spacer width implies larger potential decay V$_S$ in the undoped layer, N$_S$ decreases with increasing L$_S$. An increase of quantum well width with the same value of L$_s$ results in an increase of 2D electron concentration. The dots (a & b) in the figure show results obtained in [5]. Our calculated results are found to agree with the previous work of [5]. The high concentration of two dimensional electron gas is due to the quantum size effect in the delta doped region and spatial localization of donor impurities [11]. The nature of variation can be explained in a manner similar to the work reported in [10].

Fig. 4 shows the variation of ac mobility (μ_{ac}) and phase angle with frequency of the applied electric field for typical biasing field of $1\text{x}10^5$V/m at 77K. The ac

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mobility is found to be higher for the delta doped QW than the conventional homogeneously doped QW and it is due to more pronounced increase in ac mobility with enhanced carrier concentration in the former. The phase angle increase significantly beyond 30 GHz and is found to be higher for delta doping than conventional doping. The 3-dB cut-off frequency is 145GHz for delta doping and 199GHz for conventional doping thereby reflecting that delta doped QWs are frequency limited although their performance is better within the operating frequency limit.

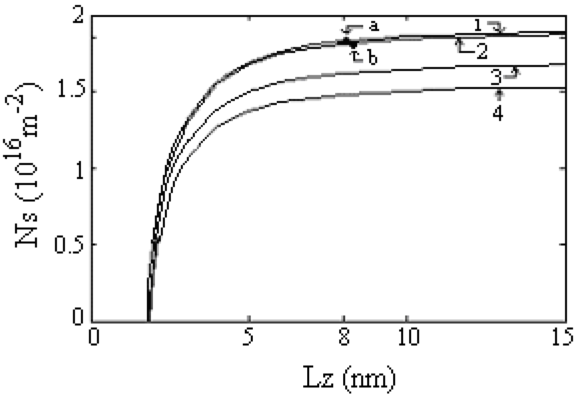

Figure 3. Variation of N_S with L_Z with a doping density of 1 x10^{16} m^{-2} & x=0.3. The curves 1, 2, 3 and 4 shows the results with Ls values of 5 nm, 7 nm, 30nm & 50 nm respectively.

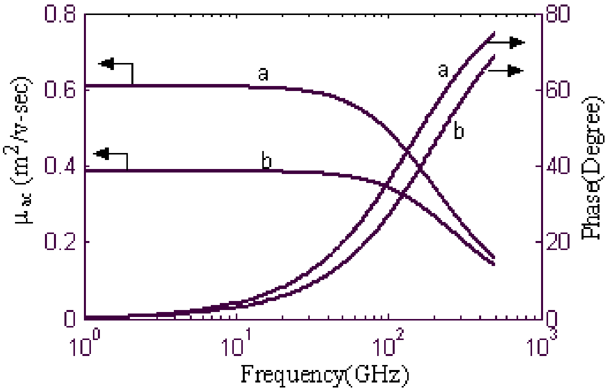

Figure 4. Variation of μ_{ac} and phase with frequency of the applied field at 77K for L_Z=12nm, L_s=7 nm, N_i=6x10^{21}m^{-3} and n^{2D}=1x10^{16} m^{-2}. The curves marked *a* and *b* represents the results for delta doped QW and conventional homogeneously doped QW

IV. CONCLUSION

In this work we have investigated the effects of delta doping on the carrier concentration and ac mobility of the two dimensional hot electrons in a square GaAs/AlGaAs QW. Our calculations show the basic effect of 2D electron concentration and mobility enhancement in GaAs QW with delta doping in the barrier AlGaAs layer. The observed increase in 2D electron concentration of the GaAs quantum well in delta doped structures is due to quantum-size effect. The use of delta doping in the barrier layer leads to enhanced 2D electron density which in turn enhanced the carrier mobility in the QW thereby establishing the scope of getting high speed devices with delta doping.

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