Effect of the hydrostatic pressure on the electron mobility in delta-doped systems

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Abstract. The influence of hydrostatic pressure on the electron states and low-temperature mobility in n-type GaAs δ-doped single quantum wells is studied. Values of hydrostatic pressure consider are below the so-called Γ–X crossover, keeping all attention in the electronic properties at the Brillouin zone center. The effect of the pressure on the electron mobility is described via a relative quantity that is proportional to the ratio between \( P \neq 0 \) and zero pressure results. Calculation is performed using an analytical description of the potential energy function profile, based on the Thomas-Fermi approach, taking explicitly into account the dependence upon \( P \) of the main input parameters: effective masses and dielectric constant. The relative mobility increases for higher values of \( P \). The cases of zero and finite -although small- temperature are studied, showing that the influence of \( T \) is mainly to lower the values of the relative mobility in the entire range of \( P \) considered. Numerical results are reported for a two-dimensional density of ionized impurities equals to \( 7.5 \times 10^{12} \text{ cm}^{-2} \).

1. Introduction

Delta-doped quantum wells (DDQW) provide the possibility of having two-dimensional conductive channels with a high density of charge carriers. In the particular case of GaAs-based systems, the n-type DDQW have been fabricated using Si atoms as donor impurities[1, 2].

Among the theoretical studies devoted to investigate the properties of the electron states in δ-doped systems one finds two main trends. In one of them, the coupled one-dimensional Schrödinger and Poisson differential equations are solved self-consistently (see for instance the references [3, 4, 5]). The other approach uses a quasi-classical scheme in which an analytical expression for the energy band potential profile is derived within the one-dimensional Thomas-Fermi local-density-functional approximation[6, 7]. Then an effective mass Schrödinger equation is solved in order to obtain the corresponding subband structure in the well.

It is known that the application of hydrostatic pressure to a crystal results in a modification of its electronic properties. This is mainly due to the deformation of the interatomic bonds[8]. There are previous reports on the influence of the hydrostatic pressure in GaAs-based n-type DDQW. In particular, a study was performed on the possibility of the formation of a high density two-dimensional electron gas associated to X-states in the conduction band, above a certain pressure threshold[9]. A different kind of investigation has shown that it may occur a pressure-induced transition to a semi-insulating state in a δ-doped system in GaAs for values of...
$P$ around 2 GPa. In this phenomenon, the participation of states within the energy gap related to DX impurity centers seem to play a fundamental role.[10].

Figure 1. Potential well profile and single electron states in a single GaAs DDQW for $n_{2d} = 7.5 \times 10^{12} \text{cm}^{-2}$.

In the present work we are aimed to study the effect of the hydrostatic pressure on the electron states in the conduction band of single DDQW of type $n$ in GaAs by exploiting the advantages of the Thomas-Fermi approach. The obtained energy spectra will be used as a key element to calculate the relative mobility as a function of $P$. This is a quantity which is given by the ratio between the low temperature two-dimensional electron mobilities corresponding to the case including pressure and that without it. For the moment, we restrict ourselves to consider values of $P$ below the point of transition from the direct to the indirect energy gap regimes, induced by pressure in GaAs. Besides, we explore the influence of finite temperature, although only limited to small values which do not threaten the validity of the approximation.

2. Model and results
As mentioned above, the calculation of the single electron states in GaAs $n$-type DDQW is carried out by solving a single band effective mass Schrödinger equation with a V-shaped Thomas-Fermi potential. For details of this potential function and its derivation, references [6, 7] are referred. The expression for this function is

$$V(z) - E_F = -\frac{\alpha^2}{(\alpha |z| + z_0)^4};$$

(1)

where $E_F$ represents the Fermi level in the system, whereas the parameters $\alpha$ and $z_0$ are given by:

$$\alpha = \frac{1}{2} \frac{m^*}{\epsilon_0^2}$$

$$z_0 = \frac{1}{2} \alpha$$
Figure 2. The variation with hydrostatic pressure of the confined energy levels in a single GaAs DDQW for \( n_{2d} = 7.5 \times 10^{12} \text{ cm}^{-2} \).

\[
\alpha = \frac{e^2 m^*^{3/2}}{\epsilon 15\pi \hbar^3},
\]
\[
z_0 = \left( \frac{2e^2 \alpha^3}{\pi \epsilon n_{2d}} \right)^{1/5}
\]  \hspace{1cm} (2)

Figure 1 shows a schematic representation of both the potential well profile and subband states. The results are presented for \( P = 15 \text{ kbar} \) and a density of ionized impurities \( n_{2d} = 7.5 \times 10^{12} \text{ cm}^{-2} \). The variation of the values of each energy level confined in the DDQW as a function of \( P \) is presented in the figure 2.

The inclusion of pressure effects is made via the variation of the main input parameters upon \( P \) \cite{12}(see Table 1). For both conduction band minima, the following relation -including temperature- holds;

\[
E_{\text{gap}}(P) = E_1 + \beta P + \alpha \frac{T^2}{(T + 204)}
\]  \hspace{1cm} (3)

On the other hand, the variation of the static dielectric constant is given by

\[
\epsilon = 12.74 e^{[0.4 \times 10^{-5} (T-75.6) - 1.67 \times 10^{-3} P]},
\]  \hspace{1cm} (4)

and the corresponding effective masses are

\[
m_{\Gamma-\text{GaAs}} = \left[ 1 + \frac{2 \times 7510}{E_{\text{gap-\Gamma-GaAs}}(P)} + \frac{7510}{E_{\text{gap-\Gamma-GaAs}}(P) + 341} \right]^{-1} m_0,
\]  \hspace{1cm} (5)
Figure 3. Relative electron mobility for a single GaAs DDQW with $n_{2d} = 7.5 \times 10^{12} \text{ cm}^{-2}$ as a function of hydrostatic pressure for different values of temperature. Reference values are taken for $P = 0$ and $T \neq 0$. The curves from top to bottom correspond to $T = 4, 3, 2, 1, 0 \text{ meV}$, respectively.

Table 1. Parameters used in the present calculations.

| Parameter          | $\Gamma - \text{GaAs}$ | $X - \text{GaAs}$ |
|--------------------|-------------------------|-------------------|
| $E_1$ (meV)        | 1519                    | 1981              |
| $\alpha$ (meV/K)   | -0.5405                 | -0.460            |
| $\beta$ (meV/kbar) | 10.7                    | -1.4              |
| $A_{(\parallel/\perp)}$ | 1.3/0.26               |                   |

\[ m_{X, \Theta} (\Theta) = (A_{(\Theta)} + 6.15 \times 10^{-3} P - 1.22 \times 10^{-5} P^2) m_0. \]  

The expression for the relative mobility can be written as [12, 13]:

\[ \mu_{\text{rel}} = \mu^{n_{\delta,P=0,T\neq0}}_{\Theta} = \frac{\int \mathcal{I}_{R^2} \rho_{e}^{n_{\delta,P=0,T\neq0}}(z') \rho_{\text{imp}}^{n_{\delta,P=0,T\neq0}}(z) |z - z'|dzdz'}{\int \mathcal{I}_{R^2} \rho_{e}^{n_{\delta,P=0,T\neq0}}(z') \rho_{\text{imp}}^{n_{\delta,P=0,T\neq0}}(z) |z - z'|dzdz'} \]  

Then, for calculating the corresponding relative conductivity we use

\[ \sigma_{\text{rel}} = n_{\text{rel}} \mu_{\text{rel}} \]

\[ n_{\text{rel}} = \frac{n_{\rho=0,T\neq0}}{4} \]
Figure 4. Relative electron conductivity for a single GaAs DDQW with $n_{2d} = 7.5 \times 10^{12} \text{ cm}^{-2}$ as a function of hydrostatic pressure for different values of temperature. Reference values are taken for $P = 0$ and $T \neq 0$. The curves from top to bottom correspond to $T = 4, 3, 2, 1, 0 \text{ meV}$, respectively.

Figure 3 (Figure 4) shows the values of $\mu_{rel}$ and $\sigma_{rel}$, respectively, obtained for the above mentioned DDQW system. It can be seen that, when compared with zero pressure conditions, the effect of the hydrostatic pressure is to increase the mobility of the electrons in the system. The conductivity increases as well; but it does it at a slower pace. This is a result of the modulation coming from the dependence of the relative density of charge carriers upon $P$. On the other hand, temperature is included going from 0 to 60 K. The effect of the increment in $T$ is to slow down the increasing of the relative mobility as a function of $P$. The same result can be readily seen for the relative electron conductivity from the figure 4.

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