Magnetotransport in Al_{x}Ga_{x-1}As Quantum Wells with Different Potential Shapes

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We compare the transport properties for triangular, parabolic and cubic quantum wells. We calculate the transport mobility for electrons belonging to the different subbands. We obtain the energy spacing between first and second subbands from the electron sheet density and compare results for different potential profiles. We find that experimental results are in quantitative agreements with our calculations.

Keywords: Al_{x}Ga_{x-1}As; Transport properties; Quantum wells

I. INTRODUCTION

Recent progress in Molecular Beam Epitaxy (MBE) growth methods has made possible the creation of electronic systems with unusual and interesting properties. Well-known examples are double quantum wells, quantum dot array in different configurations and combination of layers and quantum dots are double quantum wells, quantum dot array in different methods has made possible the creation of electronic systems. The energy levels the energy levels are evenly spaced. The energy level of the quantum number. For the parabolic well of infinite height the potential is a quadratic function of position in the well for triangular and parabolic quantum wells (b) before illuminations (n_{s} = 2.4 \times 10^{11} cm^{-2}). The effective thickness of the electronic slab can be obtained from equation \( W_{eff} = n_{s}/n_{w} \). For partially filled quantum well \( W \) is smaller than the geometrical width of the well \( W \). We varied the electron sheet density by illumination with a red light-emitting diode.

![Image of potential and electron density curves](image_url)

FIG. 1. Total potential (solid line) and electron density (dashes) as a function of position in the well for triangular (a) and parabolic quantum wells (b) before illuminations (\( n_{s} = 2.4 \times 10^{11} cm^{-2} \)).

Table 1. Comparison of the triangular and parabolic quantum wells for \( n_{s} = 2.4 \times 10^{11} cm^{-2} \). N is the number of occupied subbands.

<table>
<thead>
<tr>
<th>Sample</th>
<th>N</th>
<th>( E_{F} - E_{1} )</th>
<th>( E_{F} - E_{2} )</th>
<th>( E_{F} - E_{3} )</th>
<th>( \Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>parabolic</td>
<td>3</td>
<td>4.2</td>
<td>2.85</td>
<td>0.56</td>
<td>819</td>
</tr>
<tr>
<td>triangular</td>
<td>1</td>
<td>7.63</td>
<td>-</td>
<td>-</td>
<td>150</td>
</tr>
</tbody>
</table>
We performed full self-consistent calculations of the total potential, envelope wave functions, the eigenvalues energies and electron density in quantum wells with different shapes following a procedure similar to those used for parabolic quantum wells \cite{5, 6}. Figs. 1 and 2 show the electron density profile and total potential for triangular, parabolic and cubic quantum wells. We may see that the electronic slab width in parabolic quantum well is wider than in triangular well for the same carrier density. For cubic profile the quantum well is almost full for low electron density, therefore we are not able to do such comparison. The density profile depends on the number of substantially occupied subbands: when only one subband is occupied, the density profile is sharply peaked, as we see for triangular well. The table 1 summarize the results of the calculations of the Fermi level for different subbands in parabolic and triangular wells.

We also calculate single particle relaxation time and transport relaxation time due to the background impurity doping. It is worth to note that the single particle relaxation time, or quantum time describes the decay time of one-particle excitations and give rise to the renormalization of the density of states in contrast to the transport relaxation time, which describes the mobility of an electron gas. The quantum times are obtained by numerical integration the squared matrix elements over the allowed scattering vector using self consistent calculated wave function. Screening of the impurity scattering potential in the presence of the 2D electron gas is included within the Thomas-Fermi approximation. A detailed calculation of the quantum and transport times should include the different scattering mechanism such as homogeneous background scattering, interface roughness scattering and alloy disorder scattering. The scattering time contains many parameters, such as concentration of the background impurities, which can be enhanced in parabolic well due to the greater reactivity of Al with oxygen, and roughness of the interfaces.

![Figure 1](image1.png)

**FIG. 1.** Total potential and electron density for triangular, parabolic and cubic quantum wells.

![Figure 2](image2.png)

**FIG. 2.** Total potential (solid line) and electron density (dashes) as a function of position in the well for $U(z) = U_0 |z/W|^{3/2}$ quantum well, $n_s = 0.6 \times 10^{11} \text{cm}^{-2}$.

We do not attempt to calculate all scattering mechanisms accurately, because we are only interested its density profile behaviour. Since the wavefunction in our structures are located mostly in the center of the well we ignore the remote impurity scattering mechanism and suppose that the background impurities should be a major scattering mechanism in this case. It is worth to note that in the multi-subband systems the intersubband scattering starts to play very important role. For a system with $N$ subbands occupied the quantum time is given by

$$1/\tau_q^i = \sum_{j=1}^{N} P_{ij},$$

where $P_{ij}$ is the transition rate for an incident electron in the $i$ into $j$ subband averaged over the allowed scattering vector. It is worth to note, that for the transport time equation (1) is not valid.
The transport life time $\tau_{tr}$ has a more complicated form and can be obtained from the Boltzmann equation [7]:

$$k_i\tau_{tr} = \sum_{j=1}^{N} (K_{ij})^{-1} k_j. \tag{2}$$

where the scattering matrix $K_{ij}$ is defined as:

$$K_{ij} = \sum_{j=1}^{N} P_{ij}^0 \delta_{ij} - P_{ij}^1. \tag{3}$$

The coefficient $P_{ij}^0$ is the transition rate integrated over the allowed scattering vectors, and $P_{ij}^1$ is the first component of the Fourier transform of this transition rate. The intersubband scattering terms appear both in the diagonal and off-diagonal matrix elements. However, our system is symmetrical and the intersubband scattering between subbands of different parities vanishes. We invert the matrix $K_{ij}$ numerically, and obtain the transport life time for electrons in each subband. The effective average mobility is given by:

$$\mu = \sum_{j=1}^{N} n_j \mu_{tr}^j / n_s. \tag{4}$$

where $\mu_{tr}^j = (e/m)\tau_{tr}^j$. We fit the calculated mobility to the measured one for parabolic well and obtain background impurity concentration $N_{imp} = 1.2 \times 10^{14} cm^{-2}$.

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III. CONCLUSION

We report the comparison of the transport properties for triangular, parabolic and cubic quantum wells. We calculate the transport mobility for electrons belonging to the different subbands and find that triangular well has higher mobility. In the presence of an electric field the minimum of the confining potential may be displaced with the center of the well, whereas the implicitly of the envelope of the wave function is conserved. This particular property of the partially filled triangular well makes it suitable for the practical realization of the electronic devices based on the manipulation of the g-factor for spintronic application[8].

Acknowledgments

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