LINESHAPE OF THE RESISTANCE RESONANCE IN COUPLED QUANTUM WELLS

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Details of the resistance resonance effect in strongly coupled quantum wells are measured over a wide range of densities. The shape of the resistance resonance curve is described by a simple model. The fit provides a new method for determination of the coupling energy between the two quantum wells.

1. Introduction

The resistance resonance effect based on the quantum-mechanical concept of nonlocality was demonstrated recently in a system of two coupled quantum wells (QWs)[1]. It was shown that the parallel resistance of the wells, whose mobilities differ, exhibits a maximum when the potential profile is symmetric. Top and the bottom gates were employed in the experiment to independently adjust the densities in the two wells. The magnitude of the observed resistance peak agrees with a simple theoretical expression, and is determined from the ratio of the mobilities. Recently the problem of the resistance resonance in two coupled quantum wells has been treated theoretically[2] and more general approach which considered the problem as a special case of laterally inhomogeneous quantum transport has been presented. However, this formalism does not lead to an explicit expression of the resistance variation vs. applied gate voltage, and more detailed calculations are required to make a comparison between theory and the experiment possible. In this paper we study the lineshape of the resistance resonance peak. We describe a simple model which fits the parallel resistance in the entire range (until full depletion of both wells) of applied gate voltages. The model and experimental data are consistent and the parameters used are similar to estimates based on the geometry of the potential profile and the calculated gate capacitances.

2. Sample Structure

An MBE grown GaAs/AlGaAs heterostructure (not shown, see Ref.1 for details), resulted in the electron conduction band diagram shown in Fig.1. Two quantum wells 140Å each separated by a 28Å (40Å in ref.1) barrier were doped with radically different carrier densities provided by varying the thickness of the AlGaAs spacer layers from each QW to the delta-doped layers.

The difference in mobilities of QWs in the structures of Ref.1 was obtained by a light Si doping introduced directly into one of the wells. However, it effected the mobilities in both wells keeping their ratio small. The mobility difference in the present structure was achieved by introducing half of a monolayer of AlGaAs in the middle of the bottom well. Two gates, top and bottom, allowed the carrier concentration in each well to be independently controlled.

3. Model of the Resistance Resonance

Let us start with two uncoupled QWs having subband energies E_{f1} and E_{f2} and associated mobilities μ_1 and μ_2. For simplicity, let 1 represent the top well and 2 the bottom. When two such wells become coupled we obtain two subband energies, λ_A and λ_S which can be expressed through their initial subband energy values (E_{f1}

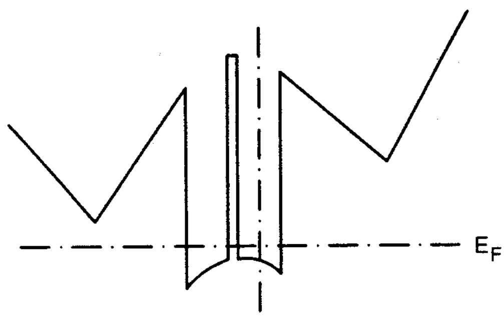

Figure 1: Conduction band diagram of two coupled quantum wells. A dashed line through the middle of the right well represents half a monolayer of AlGaAs.

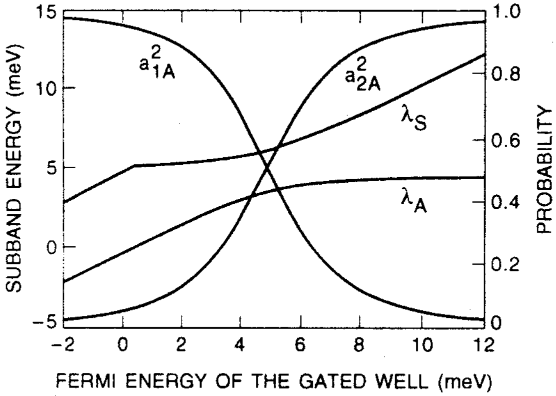

Figure 2: Subband energies and occupation probabilities vs. E_{f2} for $E_{f1}=4.75$. E_{f1} and E_{f2} represent the subband energies in each corresponding well when the coupling is ignored.

and E_{f2} for uncoupled wells) and the potential profile parameters. The indices A and S are for antisymmetric and symmetric states. If the coupling energy V and overlap integral t for initial uncoupled wavefunctions are known we can exactly calculate the subband energies λ_A, λ_S and the projections, a_{1A}, a_{2A}, a_{1S} and a_{2S}, where A and S are as before and the numerical index denotes the well, of the wavefunctions on each well. The square of these projection gives the probability of an electron belonging to a certain subband to be in a given well.

Fig.2 shows the variation of both subband energies λ_A, λ_S, and the probabilities a^2_{1S} and a^2_{2S} as a function of E_{f2} for a given E_{f1}. If we consider only electrostatics, the bottom (top) gate bias affects the carrier density only in the bottom (top) well, since the electric field is completely screened by the well (until it is fully depleted). Note that the quantum capacitance effect[3] which leads to a small penetration of the electric field does not enter in the case of two QWs. However, the quantum coupling leads to a small variation of a charge density in a second well when the gate voltage is applied to the first well in the vicinity of the resonance. In this region the depletion should be calculated self-consistently. It is a second order effect which is beyond the scope of the major effect described here. Neglecting above mentioned correction, variation of the bottom (top) gate voltage is, therefore, equivalent to a corresponding variation of E_{f1} (E_{f2}).

The scattering rate for electrons in each subband is given by the sum of the scattering rates in each well multiplied by the probability to occupy that well. The effective mobility for each subband can be expressed as $\mu_A(\lambda_A)^{-1}=a^2_{1A}\mu_1(\lambda_A)^{-1}+a^2_{2A}\mu_2(\lambda_A)^{-1}$. A similar expression holds for the symmetric configuration. The number of carriers in each subband is given by $n_A=\lambda_A N$, where N is the 2D density of states. Since the total conductance is given by the sum of conductances for each subband the resistance may be written as $R=\sigma^{-1}=(en_A\mu_A+en_S\mu_S)^{-1}$.

4. Experimental Data and Discussion

The resistance of the two wells vs bottom gate bias for the variety of upper gate voltages is presented in Fig. 3. The resistance peak is much higher and broader than the one reported earlier[1], indicating a larger mobility ratio and stronger coupling between wells. In order to compare experimental data with the theory outlined above we have converted the units of the gate voltage applied to the bottom gate into the units of the subband energy in the bottom well. This conversion was done using the geometrical value of the capacitance between the gate and the well and measuring the voltage required to deplete this well.

The theoretical curves shown in Fig. 4 were obtained using the following parameters determined for all

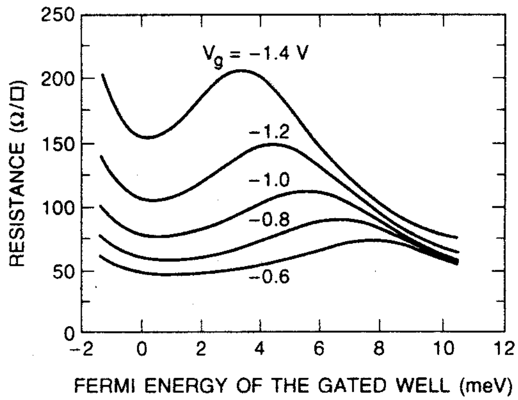

Figure 3: Resistance vs. gate bias in units of bottom well subband energy.

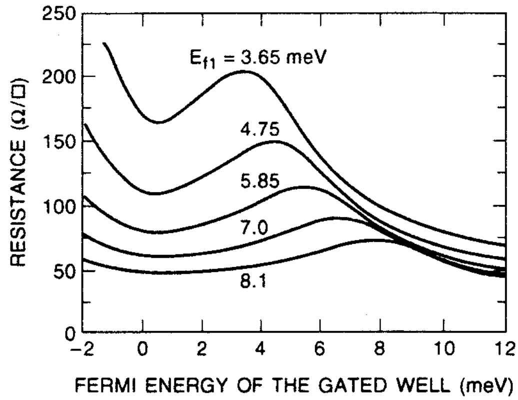

Figure 4: Calculated resistance vs. bottom well subband energy.

curves: $\mu_1(\lambda_A)=6.4x10^5(.64+.05\lambda_A)$, $\mu_2(\lambda_A)=\mu_1(\lambda_A)/6.4$, t=0.035, V=-1.2 The only variable parameter for each curve is E_{f1} which is proportional to the voltage applied to the top gate. The ratio between the shifts in E_{f1} and the top gate voltages are consistent with the top gate geometrical capacitance. In general the fit is quit good. The small deviations are most probably due to oversimplified relationship between the density and the mobility which we used in our model. The shape of the theoretical curve in the range of resistance peak is very sensitive to the parameter V, therefore we argue that the resistance resonance effect can be used as a method to determine the coupling energy between QWs.

5. Conclusion

We have shown that introduction of neutral impurities into one of two closely spaced QWs leads to dramatically different mobilities in the two wells. The large mobility ratio produces a pronounced resistance resonance. The lineshape of the resistance resonance effect can be well described by the model based on the existence of extended electronic states in both wells. In particular, the model is quite sensitive to the coupling between the two wells and provides an excellent experimental measure of this quantity.

Acknowledgement-

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2. R. Lenk, submitted to *Solid State Communications* (1991).
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