Resistance Resonance in Coupled Potential Wells

Alexander Palevski, Fabio Beltram, Federico Capasso, Loren Pfeiffer, and Kenneth W. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
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A new *resistance resonance* effect based on the quantum-mechanical delocalization of electrons in a symmetric-double-well potential is presented. We show that changing the symmetry of the potential profile gives rise to a resistance peak if the transport properties of the two wells are different. The proposed effect is demonstrated experimentally in semiconductor heterostructures.

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The validity of the quantum-mechanical description of physical systems has been successfully tested in many different areas of physics. Some of these experiments, such as electron interference from double slits or electron diffraction on crystals, have a particular tutorial value due to their resemblance to wave-optics experiments. Even today, the *direct* experimental verification of basic quantum-mechanical concepts, such as the absence of classical trajectories, attracts considerable attention. In solids, there have been a number of predicted and observed effects demonstrating the quantum nature of electrons, among them the Aharonov-Bohm effect, universal conductance fluctuations, localization, quantized Hall effect, etc. In this Letter we report a new effect which unambiguously manifests the wave properties of electrons in solids.

Let us consider a system of two quantum wells (QWs) separated by a potential barrier U of width W [Fig. 1(a)]. If the potential profile is very asymmetric, so that corresponding energy eigenvalues in each well solved independently differ by more than their coupling energy $\Delta\epsilon$, the system can be viewed approximately as consisting of two uncoupled wells with eigenstates localized in each well. For an exactly symmetric system, on the other hand, the eigenstates will be described by symmetric and antisymmetric functions extending in both wells with eigenvalues separated by $\Delta\epsilon$. The probability of finding an electron in a given eigenstate in either well will be the same. Thus, as the symmetry of the wells varies, as a result, for example, of an external perturbation, electrons being shared initially by both wells are eventually localized in separate wells. This is a well-known quantum-mechanical effect[1] without any classical analog.

The above discussion can be extended to the case of two interacting two-dimensional QWs in a heterostructure. Let us consider the resistance of two such QWs connected in parallel. When electrons are localized in separate wells, the resistance can be determined using the classical rule for a parallel configuration. In particular, in the case of very different mobilities, the combined resistance should approach that of the higher-mobility well. On the contrary, at resonance (symmetric case), since electrons are shared by both wells, the total resistance should approach that of the well with poor mobility. This implies that such QWs will exhibit maximum resistance when symmetry is achieved. It is very important to understand that this effect *is not* based on *real-space transfer* of charge between the two wells. On the contrary, it is exclusively based on the wave nature of electronic states which, at resonance, extend into both wells, therefore probing the transport properties of both.

Let us consider a structure consisting of two QWs separated by a thin barrier [Fig. 1(b)]. Ohmic contacts are provided to the two-dimensional electron gases (2DEGs) in parallel and a Schottky gate is deposited on

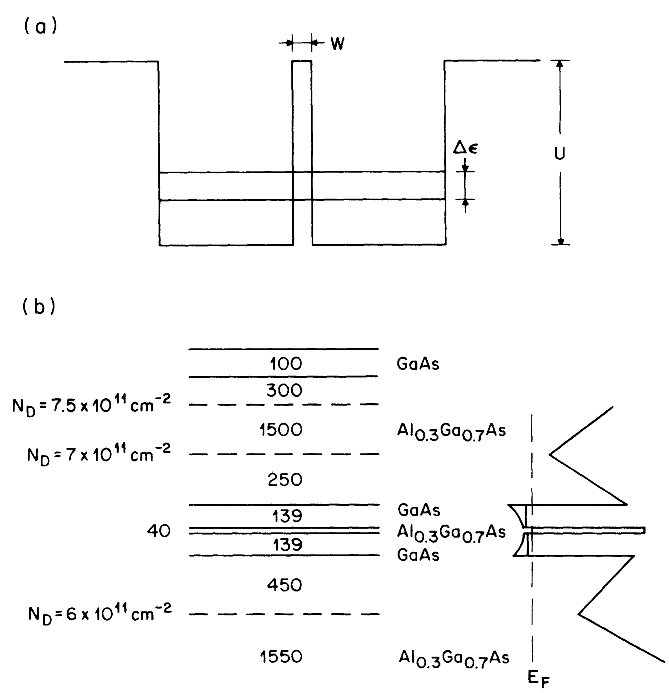

FIG. 1. (a) Schematic potential profile of a double quantum well; $\Delta\epsilon$ is the energy separation of the ground-state doublet. (b) Sample structure and equilibrium conduction-band diagram. All thicknesses are given in angstroms. The dashed lines represent the positions of the δ-doped planes; the rest of the structure is undoped.

the sample surface. The resistance of the 2DEGs is monitored as a function of the gate bias. The latter controls the symmetry of the double-well-potential profile. By deliberately making the electron mobilities very different in the two wells, a peak in resistance should appear as the resonant configuration of the wells is realized.

In reality, of course, it is very difficult to produce two closely spaced QWs with very different mobilities. Thus we should estimate the size of the effect for an arbitrary ratio of mobilities. Assuming that the coupling energy $\Delta\epsilon$ is much smaller than the Fermi energy of the 2DEG, E_F, we can say that the two-dimensional electronic density n is the same in the wells both at resonance and off resonance (in a neighborhood of gate voltages corresponding to $\Delta\epsilon$). Denoting the mobilities by μ_1 and μ_2 (where the index 1 refers to the top QW), we can express the 2DEG resistances as $R_1=(\mu_1 ne)^{-1}$ and $R_2=(\mu_2 ne)^{-1}$. The total resistance off resonance will be given by

$$R^{\text{off}}=1/ne(\mu_1+\mu_2)\,. \tag{1}$$

At resonance, the system should be viewed as one having an electron density of $2n$, with a mobility μ_0 satisfying $\mu_0^{-1}=\frac{1}{2}(\mu_1^{-1}+\mu_2^{-1})$. Here we used the assumption that the scattering rates in the wells are addable. This approximation is valid if $\Delta\epsilon$ is greater than the energy broadening due to scattering. Since the scattering rate is dominated by the momentum relaxation times τ_1,τ_2 in the two wells, we must have $\hbar/\Delta\epsilon \ll \tau_1,\tau_2$. For $\Delta\epsilon \sim 1$ meV, this condition is satisfied for mobilities larger than $\sim 2\times 10^4$ cm^2/Vs, a condition verified in our experiments. At resonance, the resistance will be given by

$$R^{\text{res}}=(1/4en)(\mu_1+\mu_2)/\mu_1\mu_2\,, \tag{2}$$

and the relative size of the resonance peak by

$$\frac{\Delta R}{R}\equiv\frac{R^{\text{res}}-R^{\text{off}}}{R^{\text{off}}}=\frac{(\mu_1+\mu_2)^2}{4\mu_1\mu_2}-1=\frac{(r+1)^2}{4r}-1\,, \tag{3}$$

where $r\equiv\mu_1/\mu_2$. Even when the mobilities are not very different one should observe a noticeable peak in the resistance; for example, for $r=2$, $\Delta R/R=0.125$.

Our samples, whose structure is shown in Fig. 1(b), were grown by molecular-beam epitaxy[2] in the AlGaAs material system. Electrons were introduced in the wells by selectively doping the barriers (modulation doping[3]). The difference in the mobilities was obtained by introducing an enhanced amount of impurities (Si, 10^{16} cm^{-3}) in one of the QWs. Standard fabrication methods were used to pattern 10-μm-wide and 200-μm-long channels and Au/Ge/Ni Ohmic contacts were provided to them. The Schottky gate covered the major part (75%) of the channels. The modulation doping of the first channel was made higher than the second. This produces an asymmetry at zero gate bias as shown in Fig. 1(b); our self-consistent calculations show that at zero bias the states are localized in the individual wells and that their energy-level difference is 7 meV. This initial asymmetry allowed us to restore a symmetric potential profile (delocalized configuration) by operating the Schottky gate junction in reverse bias (negative gate voltage).

The proximity of the QWs prevents the formation of Ohmic contacts to each 2DEG separately, so the individual resistances cannot be measured. However, it is possible to characterize each QW individually, thanks to their sequential depletion caused by the gate electric field. If V_{g_1} is the gate voltage required to deplete the first QW and V_{g_2} the gate voltage depleting both QWs (i.e., the bias at which the channel conductivity vanishes), the ratio of densities at $V_g=0$ is given by $n_1/(n_1+n_2)=V_{g_1}/V_{g_2}$. V_{g_1} will be observed in the channel (drain-to-source) resistance versus gate voltage curve as a plateau. The appearance of this plateau is due to the degradation of the mobility of the first QW near complete depletion so that for a certain gate bias range, the first channel is shorted out by the second, undepleted, channel which is retaining its original full conductivity. The detailed shape of this plateau region is a function of the relative conductivities and interface characteristics. Moreover, the value of conductance at the plateau measures the conductance of the second 2DEG (first QW depleted). Finally, since, as discussed above, at zero gate bias the QW states are localized, the measured zero-gate-bias channel resistance gives the value of the parallel configuration, $1/e(n_1\mu_1+n_2\mu_2)$. From the expression for R_2, knowing n_1/n_2 at $V_g=0$, we can estimate μ_1/μ_2. At this point, via Eq. (3), the size of the effect can be estimated.

The 2DEGs resistance and its logarithmic derivative as a function of the applied gate voltage are presented in Fig. 2. The plateau region is clearly observed at $V_{g_1}\approx -2.5$ V (shown by the upward arrow); depletion of both wells occurs at $V_{g_2}\approx -4.2$ V (not shown). Although, as followed from our data analysis, the ratio of mobilities was not large, the resistance peak due to the resonance at $V_g\approx -0.8$ V is well resolved. At this gate voltage, symmetry in the double-well-potential profile is achieved and the wave-function delocalization discussed earlier is manifested by the appearance of the peak. The position of the latter, as well as its size, is in good agreement with our theoretical estimates. The ratio of carriers measured at 4.2 K is $n_1/n_2\approx 1.5$ and the estimated mobility ratio[4] is $r=\mu_1/\mu_2\approx 1.3$; $\mu_1>\mu_2$ is expected since the impurities were introduced into the second well. Equation (3) gives for the resonance peak $\approx 1.7\%$. The measured size of the resonance is $\gtrsim 0.01$.

Further verification of the nature of the observed effect was provided by a temperature-dependence study. The size of the effect is monotonically decreasing as the temperature is increased and cannot be resolved at

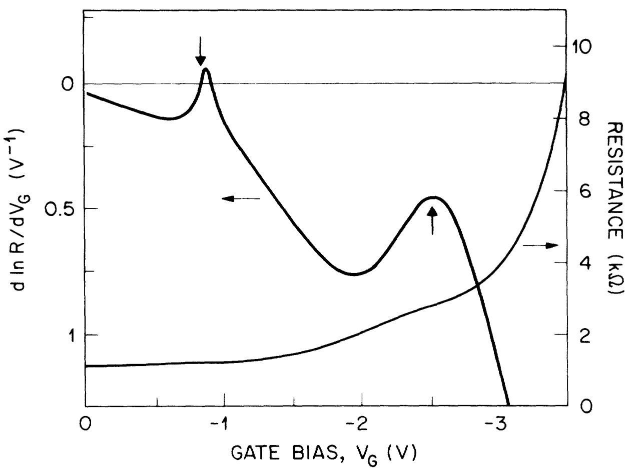

FIG. 2. Resistance and its logarithmic derivative vs gate bias at 4.2 K. The bias across the channel was 150 mV. The downward arrow indicates the position of the resistance resonance, the upward one shows the starting point of the second well depletion.

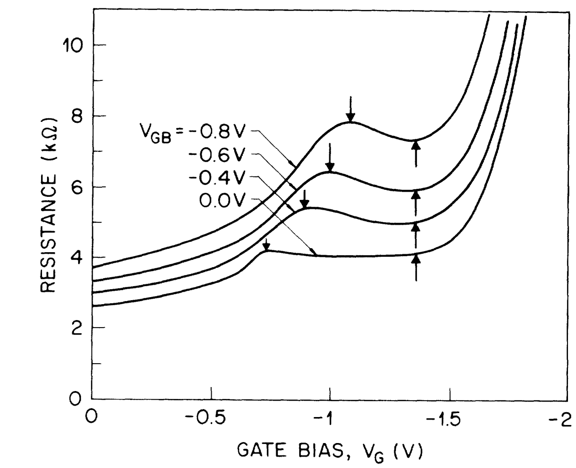

FIG. 3. Resistance vs gate bias characteristic (back-gated structure) at 4.2 K at different values of the back-gate bias (V_{GB}). The bias across the channel was 4 mV. The downward arrows indicate the position of the resistance resonance; the upward ones show the starting point of the second well depletion.

$T \gtrsim 50$ K. The plateau region which separates the depletion of the first and second QWs, on the contrary, vanishes at much higher temperature (it is still observed at $T=100$ K). This definitely indicates that the resonance and the plateau have different origins. The decrease of the resonant peak is expected when $\Delta\epsilon/kT < 1$. In our structure at zero bias, we calculated $\Delta\epsilon \approx 1$ meV, by solving numerically the Schrödinger equation for the double-well potential. Therefore the decrease is expected for $T \gtrsim 12$ K. At $T \approx 50$ K the effect is smeared out since our signal-to-noise ratio is ~ 5. On the other hand, the disappearance of the plateau has a purely electrostatic nature and it is related to the increase of the Debye length L_D at higher temperatures. When $L_D > W$ (where W is the separation between wells), the depletion of the wells will be concurrent.

To further substantiate our findings we studied the transport in another structure. It was essentially like the first one, but it was grown on doped GaAs and the impurities were introduced in the first rather than the second QW. The doped substrate was used as a back gate therefore allowing us to vary the carrier concentration in the second well. The analysis of the resistance versus gate voltage curve (see Fig. 3) indicates that the mobility ratio[4] of the first and the second 2DEG is $r \approx 0.4$ and the carrier concentration ratio $n_1/n_2 \approx 1.6$ (in this case, $\mu_1 < \mu_2$, again consistent with the position of the impurities). For this mobility ratio the effect is much more pronounced than in the previously discussed sample. The size of the effect $\Delta R/R \approx 0.2$ agrees well with the theoretical estimate 0.23. The position of the resistance peak depends on the bias of the back gate. Negative voltage applied to the back gate causes depletion of the QW next to it. This results in a shift of the peak position since the resonance condition will be realized at higher values of V_g (see Fig. 3). This sample does not show the beginning of the plateau associated with the depletion of the first QW. It is "swallowed" by the resonance peak. The end of the plateau, however, is easily identified as the bias where the resistance increases again versus V_g. It is important to note that its position is the same for all values of back-gate voltages, thus confirming that the observed shift is not related to electrostatic influence of the top and back gates but rather is due to a shift of the energy level in the second well. The width of the resonance is ≈ 200 mV in gate voltage which corresponds to a 2-meV shift of conduction-band energy in the well. This is somewhat larger than the expected coupling energy $\Delta\epsilon \approx 1$ meV. However, our estimate of the coupling energy was obtained under the assumption of zero external field. Negative bias on the gate will increase the coupling.

We also tested a sample with equal mobilities and electron densities.[5] We observed the plateau due to the sequential depletion and our analysis confirmed the symmetry of the structure as well as the equal mobilities. As expected from our model, no peak in the resistance-voltage characteristic was observed [from Eq. (3), $\Delta R/R = 0$ when $r = 1$].

In conclusion, we demonstrated a new *resistance resonance* effect based on the quantum-mechanical concept of nonlocality. We showed that a simple resistance measurement can probe the coupling strength of two QWs.

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[1]See, e.g., L. D. Landau and E. M. Lifshits, *Quantum*

Mechanics (Pergamon, London, 1977), 3rd ed., Chap. 7.

[2]L. Pfeiffer, K. W. West, H. L. Stormer, and K. W. Baldwin, Appl. Phys. Lett. **55**, 1888 (1988).

[3]R. Dingle, H. L. Stormer, A. C. Gossard, and W. Weigmann, Appl. Phys. Lett. **33**, 665 (1978).

[4]The variation in the carrier concentration from zero bias to the resonance bias can cause a variation in the value of the mobility (μ_1). We have indeed observed a small change in μ_1 which was included in the evaluation of r.

[5]The QW coupling of this structure was studied in a separate experiment using magnetotransport measurements; G. S. Boebinger, H. W. Jiang, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **64**, 1793 (1990).