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# Quenching of resonance-induced resistance in double-quantum wells in the presence of in-plane magnetic fields

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Effects of in-plane magnetic fields on the channel resistance of double quantum wells are studied for the case where impurities are introduced only in one of the wells. The resonant increase of the channel resistance caused by the gate-induced resonant coupling of two levels is found to be quenched by an in-plane magnetic field and it is successfully ascribed to the field-induced mixing of the resonantly coupled states.

Effects of an in-plane magnetic field $B\hat{x}$ on resonant tunneling in semiconductor heterostructures have been extensively studied since they provide new insights on quantum states and transport of electrons.[1] In essence, $B\hat{x}$ deflects the motion of tunneling electrons, quantizes their motion to interfacial Landau states, or makes the canonical momentum $p_y = \hbar k_y$ be replaced by $\hbar k_y - eB\Delta z$, where $\hbar$ is the reduced Plank constant, $e$ the elementary charge, $k_y$ the wave number in the $y$ direction, and $\Delta z$ the average separation between the initial and the final states in the tunneling process. As a result, the tunnel transport in double barrier diodes is modulated as the number of tunneling electrons is constrained by the conservation of energy and momentum.[2] Using this feature, complicated dispersion relations of holes in a quantum well have been obtained, for example.[3]

The resonant tunneling of a two-dimensional electron gas (2DEG) in double quantum well (DQW) structures is also modified by the in-plane field $B\hat{x}$.[4,5] Such a tunneling between two sheets of weakly-coupled 2DEG's has been studied by making an independent contact to each sheet of 2DEG in elaborate ways.[4,6] Observed characteristics reflect primarily the tunnel current perpendicular to the barrier. In the present work, we investigate parallel electron transport in intermediately coupled DQW structures, and examine how it is affected by an in-plane magnetic field. Specifically, we employ here DQW structures with an asymmetric scatterer distribution, in which the gate-controlled resonant coupling of wave functions results in the resonant change of a resistance.[7] We will show that this "resistance resonance" is quenched by the in-plane magnetic field especially when the field is applied perpendicular to the current. We present a simple model to account for this observation.

The sample employed here was grown on a semi-insulating GaAs substrate by molecular-beam epitaxy. As schematically shown in Fig. 1, it consists of two 150-Å GaAs quantum wells (QW's) separated by a 22.5-Å $Al_{0.26}Ga_{0.74}As$ barrier. At the center of the top QW, a $Si^+$ $\delta$-doping layer of $1 \times 10^{10}$ cm$^{-2}$ is inserted to make a difference between mobilities of two QW's. A Hall bar geometry 200 $\mu m$ long and 50 $\mu m$ wide was defined. A Schottky gate was then formed by the vacuum deposition of Al, and Ohmic contacts were made by alloying InSn to both QW's.

The channel resistance of the present sample was measured at 1.5 K by ac lock-in technique with a small excitation current of 10 nA, 15 Hz. In Fig. 2 the zero-field resistivity is plotted as a function of the gate voltage $V_g$ by a solid line. In this structure, $V_g$ changes not only the total electron density but it also controls the level coupling and the shapes of wave functions in the DQW. In particular, the latter influences the scattering process and modulates the channel resistance near the resonant condition. When the potential profile is asymmetric and two QW's are uncoupled, electrons confined in the undoped QW channel dominate the conductivity. At resonance, however, the wave functions of the two lowest states extend out over both QW's and overlap inevitably with the $\delta$-doped impurities. The peak of the channel resistance shown in Fig. 2 results from this enhancement of ionized impurity scattering rate for all electrons in the DQW channel.[7]

To clarify the electron population in two lowest subbands, Shubnikov–de Haas oscillations were measured at

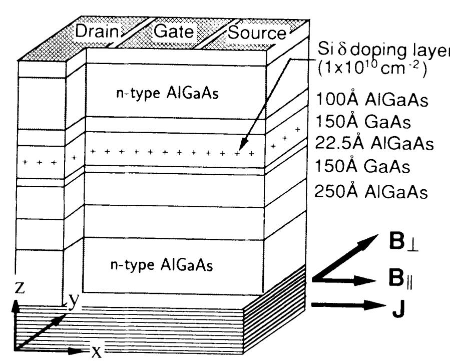


FIG. 1. The cross-sectional view of the sample structure is schematically shown. The channel is taken in the $x$ direction. An in-plane magnetic field is applied both in the $x$ and $y$ direction.

 

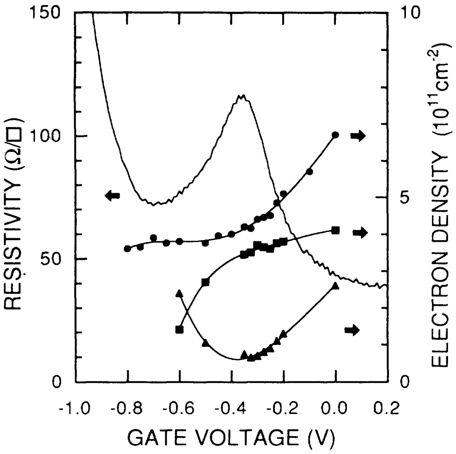


FIG. 2. The zero-field channel resistivity $\rho_{xx}$; gate voltage $V_g$ characteristic at 1.5 K is shown by a solid line. Closed circles and squares indicate the electron densities of individual subbands. Closed triangles are the difference between them.

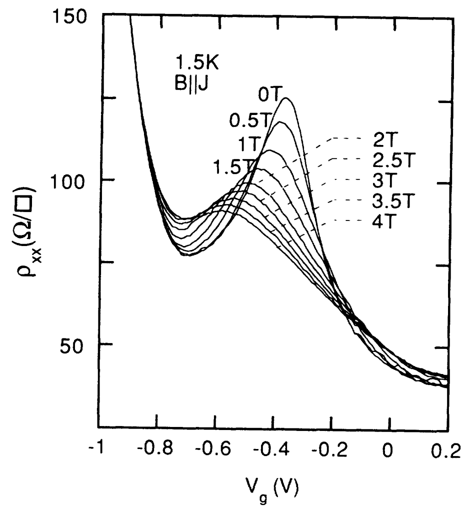


FIG. 3. The longitudinal magnetic field $B\|$ dependence of $\rho_{xx}$ plotted as functions of $V_g$.

different gate voltages. Electron concentrations $N_{s1}$ and $N_{s2}$ are evaluated from the Fourier transform, and plotted in Fig. 2. From these curves, one can readily determine the quantized levels with respect to the Fermi energy. Note that $N_{s1}$ and $N_{s2}$ (or two levels) anticross each other. The energy separation $\Delta E_{\rm SAS}$ is estimated to be 2 meV at the anticrossing point. It agrees well with the theoretical value 1.7 meV calculated self-consistently.

At $V_g = 0$ V, where electronic states are uncoupled, electron mobilities in doped and undoped quantum wells are found to be about 67 000 cm$^2$/V s and 220 000 cm$^2$/V s, respectively.[8,9] Note here that the relaxation time of each channel is sufficiently long as compared with the tunneling time. This indicates that the description of the present DQW system in terms of the coherently extended electronic states is quite valid.[10]

As described earlier, the resonant coupling in DQW structures should be influenced by a magnetic field parallel to the QW layer. This change of coupling should be reflected in the resistance peak in parallel transport as clearly as in the vertical transport experiment. One should note, however, that behavior of electrons should depend on the direction of magnetic field with respect to the current flow direction. Hence, we have studied the effect of in-plane magnetic fields for both cases where the fields are applied parallel (**B**$\|$) and perpendicular (**B**$\perp$) to the current **J**. This point will be discussed later.

To apply a magnetic field parallel to the layers precisely, the sample was fixed where the Hall voltage across the channel vanishes. At several values of the magnetic field, the channel resistance is measured as functions of $V_g$.

In Fig. 3, $\rho_{xx}$ for **B**$\|$**J** are plotted as functions of $V_g$. The resistance peak decreases with the increase of **B**$\|$, indicating that the coupling is weakened. The rate of quenching with the magnetic field is, however, rather small with the peak being visible even at 4 T. Simultaneously, the position of the peak is seen to shift toward negative $V_g$, with the peak width broadened. When $V_g$ is biased at some value in the region of off-resonance, $\rho_{xx}$ increases. This tendency is most obvious at the valley point of $\rho_{xx}$, where the second subband starts to be occupied by newly induced electrons.

For comparison, we studied the $\rho_{xx}$-$V_g$ characteristics for **B**$\perp$**J**. The result is shown in Fig. 4, where the resistance peak is found to fall down much more abruptly. The quenching rate for **B**$\perp$**J** up to ~1 T is greater by a factor of 3 than the case **B**$\|$**J**. Around 3 T, the peak structure completely vanishes. Note also that the magnetoresistance under off-resonant condition is negative, contrary to the positive magnetoresistances for **B**$\|$**J**. The shift of the peak position is also found, but is far smaller than for **B**$\|$**J**.

In the case of **B**$\perp$**J**, one must consider the possibility that the in-plane magnetic field induces the Hall electric field in the direction of the DQW potential which may lead to an excess charge transfer from one well to the other. In such a case, $\rho_{xx}$ should depend on the polarity of the magnetic field or the current because of the asymmetry of the mobilities. We found this effect to be negligible, as in dc measurements no difference was observed when the polarities of current or magnetic field

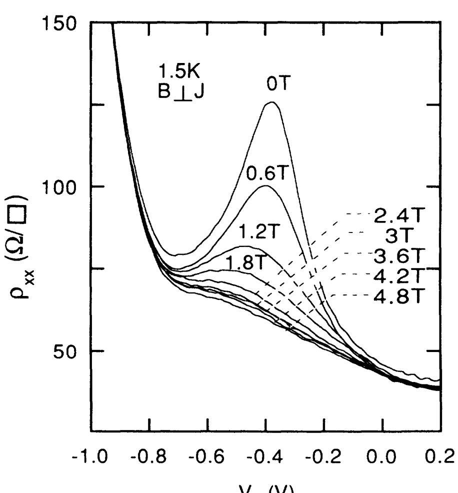


FIG. 4. The transverse magnetic field $B\perp$ dependence of $\rho_{xx}$ plotted as functions of $V_g$.

were reversed.

To examine the origin of the quenching of the resistance peak and its marked dependence on the magnetic-field orientation, we consider next the mixing of the extended eigenstates in a parallel magnetic field $\boldsymbol{B}$. As shown in Fig. 1, we take the channels in the $xy$ plane and the origin of $z$ at the center of the barrier between two QW's. The DQW potential $V(z)$ is assumed to be symmetric for simplicity. When $\boldsymbol{B}$ is in the $x$ direction, the vector potential $\boldsymbol{A}$ can be expressed as $(0, -Bz, 0)$ in the Landau gauge. In this case the motion of electrons in the $x$ direction cannot be affected by $\boldsymbol{B}$. By treating the DQW system as a unit, the $z$ component of wave functions $\psi_i(z)$ ($i$ is the index of the level) are given by solving the following Schrödinger's equation:

$$\left\{-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + V(z) - \frac{1}{2m}eBz(\hbar k_y - eBz)\right\}\psi_i(z;k_y,B) = E_i(k_y,B)\psi_i(z;k_y,B), \quad (1)$$

where $m$ is the effective mass and $E_i$ the quantized level for the $i$th subband. If a magnetic field is sufficiently low, the term $H' = -(1/2m)eBz(\hbar k_y - eBz)$ can be regarded as a perturbation. Then the wave functions $\psi_i(z)$ ($i = 1, 2$) can be expressed as linear combinations of symmetric ($|\mathrm{S}\rangle$) and antisymmetric ($|\mathrm{AS}\rangle$) states, which are the well-known eigenfunctions of the Hamiltonian with no perturbation, $H_0 = (-\hbar^2/2m)\partial^2/\partial z^2 + V(z)$. In the present case, the mixing is mainly between $|\mathrm{S}\rangle$ and $|\mathrm{AS}\rangle$ since higher excited states are separated with large energy as compared with $\Delta E_{\mathrm{SAS}}$. The mixing coefficient $c_{\mathrm{SAS}}$ is then given by

$$c_{\mathrm{SAS}} = -\left\langle \mathrm{S}\left|\frac{1}{2m}eBz(eBz - \hbar k_y)\right|\mathrm{AS}\right\rangle \Big/ \Delta E_{\mathrm{SAS}}. \quad (2)$$

When $k_y = 0$, the mixing does not occur because $|\mathrm{S}\rangle$ is even and $|\mathrm{AS}\rangle$ is odd with respect to the origin of $z$. As $k_y$ deviates from zero, the mixing increases and leads to a situation where the probability function $|\psi_i(z;k_y,B)|^2$ starts to concentrate in one QW, while that of $-k_y$ concentrates into the opposite side. When $k_y$ gets as large as the Fermi wave number $k_F$, the numerically calculated $c_{\mathrm{SAS}}$ is $\sim$1 even at $B = 1$ T. At that point, the envelope functions $\psi_i(z;k_y,B)$ are reduced to $|\mathrm{S}\rangle + |\mathrm{AS}\rangle$ and $|\mathrm{S}\rangle - |\mathrm{AS}\rangle$, which are degenerate states in isolated QW's, although the validity of this approximation must be examined.

From the above discussion, it is clear that decoupling of symmetric and antisymmetric states by the in-plane magnetic field and the subsequent decrease of the probabilities of the impurity scattering strongly depend on $k_y$, that is, these effects are reflected only on the electronic states with large value of $k_y$. As the electric field is applied in the $x$ direction in our case, the conductance is mainly dominated by the electrons with large $k_x$. Hence, the influence of $\delta$-doped impurities on the electron transport decreases only with a modest rate; this explains why the magnetic-field effect was small for $\boldsymbol{B}\|\boldsymbol{J}$.

When the in-plane filed $\boldsymbol{B}$ is in the $y$ direction, i.e., $\boldsymbol{B}\perp\boldsymbol{J}$, one can expect that the decoupling of electronic states into two isolated 2DEG's should take place most efficiently for electrons with large $k_x$. Since these electrons dominate the current transport and since electrons localized in the undoped QW are released from the $\delta$-doped impurities, the magnetic-field dependence of the magnitude of the resistance peak should be far larger in this case, which is in accordance with the experiments.

Lastly, we briefly discuss the conventional model of the 2D-2D tunneling, where a weak coupling is assumed. This model is certainly one of the simplest approaches to understand the effect of an in-plane magnetic field and also fits with many experimental situations, where the overlap between two localized states is set small enough to keep the tunnel current small and sensitive to the applied bias. The coherent tunneling in such a system is interpreted as a conservation of the energy and the *canonical* momentum; electrons at the intersection of two displaced Fermi surfaces can participate in the tunnel transfer.[5] In the present case, where a DQW with intermediate coupling strength is studied, it is better to adopt an alternative model where the delocalized eigenstates are influenced by a magnetic field discussed earlier. At the limit of a weak tunneling, both approaches lead to similar results. Hence the coupling strength is a key parameter.

Although the resistance resonance modified by an in-plane magnetic field is successfully explained by our simple model, we note here that there is another case where the phase relaxation time of the doped QW is shorter than the tunneling time. In such a case, one cannot define an ideally coupled states and, therefore, must develop more refined pictures.[9,10] This issue and a few other complicated findings, such as the shift of the resonant peak, will be discussed elsewhere.

In summary, we have shown that the resonant increase of the channel resistance in double quantum wells is quenched by an in-plane magnetic field. The quenching is much more efficient for a magnetic field normal to the current which is successfully ascribed to the magnetic-field-induced mixing of extended one-particle wave functions.

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