Resonant resistance enhancement in double-quantum-well GaAs-$Al_xGa_{1-x}As$ heterostructures

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We present a study of electron transport in coupled quantum-well structures controlled by both front and back gates. The resonant resistance enhancement is systematically investigated by varying the mobility in each quantum well. We show that a large mobility ratio between the two wells gives a large resonant resistance enhancement only when the level broadening is smaller than the symmetric-antisymmetric gap of the coupled system.

The advent of thin-layer growth of semiconductors has made it possible to design and realize new semiconductor devices based on quantum mechanics. One of the observed phenomena, which is directly related to the wave nature of electrons, is the wave-function coupling between two closely spaced two-dimensional electron gases (2DEG's). This can be obtained in systems such as double-quantum-well (DQW) structures. If the scattering in the double 2DEG system is not symmetric, an increase in resistance, i.e., resistance resonance, arises when the two 2DEG's are resonantly coupled.[1] This is because a higher mobility 2DEG, the wave function of which is localized in one of the two wells, is delocalized over both wells by hybridization at resonance, and thus suffers increased scattering in the lower mobility well. The size of the hybridization is characterized by the energy gap between the hybridized symmetric and antisymmetric states, Δ_{SAS}.

The concept of resistance resonance can be applied to the velocity modulation transistor (VMT) proposed by Sakaki and co-workers.[2,3] In this device the conductance modulation is achieved by changes to the mobility while the carrier density is kept constant. VMT operation has been achieved in single conduction channel structures,[4,5] but is hard to demonstrate in double-channel structures due to the difficulty of fabricating a back gate which can be sufficiently biased to compensate the carrier density change arising from the front-gate voltage variation.

In this paper, we describe the successful fabrication of DQW-VMT structures using the technique of molecular-beam epitaxy (MBE) regrowth on an epilayer patterned by an *in situ* focused ion beam.[6] By comparing the size of the resistance resonance among devices with different values of mobility, we show that a high-mobility ratio is not sufficient for a sizable resistance resonance effect. In addition, the mobility of both 2DEG's must be large enough that the level broadening due to scattering is smaller than Δ_{SAS}.

The modulation-doped DQW structures (Fig. 1) were grown on semi-insulating GaAs substrates by MBE. All samples consisted of two 150-Å-wide quantum wells separated by a 25-Å $Al_{0.33}Ga_{0.67}As$ barrier. Electrons in the 2DEG's were supplied by Si-doped $Al_{0.35}Ga_{0.67}As$ layers placed above and below the DQW. The whole DQW structure was then isolated by a 0.31-μm $Al_{0.33}Ga_{0.67}As$ barrier from an n^+-type GaAs back-gate layer grown underneath. Ohmic contacts to the double 2DEG's were achieved, without contacting to the n^+-type GaAs back-gate layer, using MBE regrowth on an *in situ* focused ion-beam patterned epilayer.[6] After growth, devices were processed into a Hall bar geometry with a front Schottky gate as well as the back gate. The leakage current between the back gate and the 2DEG's was less than 1 nA throughout the gate voltage range reported here. The resistance of the samples was measured using a

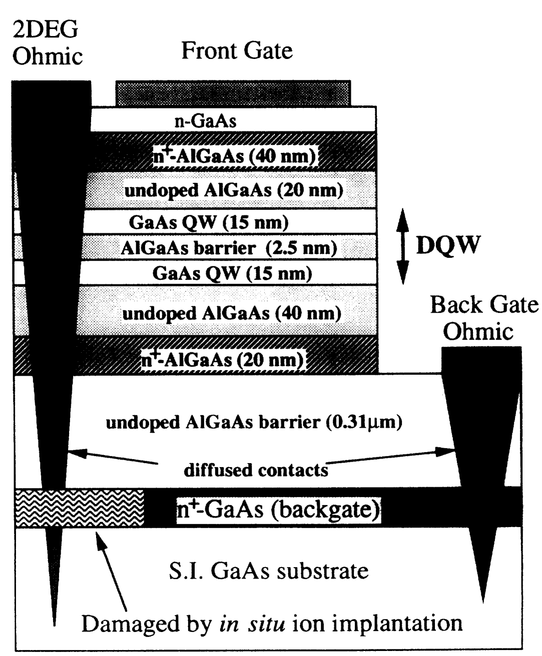

FIG. 1. Schematic cross section of back-gated DQW structure. The doping level of n^+-type $Al_{0.33}Ga_{0.67}As$ layers was 1×10^{18} cm^{-3}. An MBE regrowth on an *in situ* ion beam patterned epilayer was used to form Ohmic contacts to the 2DEG's without contacting the n^+-type GaAs back gate layer.

standard lock-in technique with a relative error ($\delta R/R$) smaller than 0.2%.

In order to achieve a large resistance resonance, a significant difference in the scattering rate between the two wells is desirable. The QW's were not intentionally doped,[3] but a mobility difference between the QW's occurred naturally due to diffusion of dopant from the n^+-type $Al_xGa_{1-x}As$ back-doped layer into the back $Al_xGa_{1-x}As$ spacer layer during MBE growth. This diffusion caused enhanced ionized impurity scattering and hence a lower mobility in the back 2DEG. In order to adjust the effect of the diffusion, we varied the growth temperature (T_g) of the lower doped layer in three samples: A ($T_g = 520\,°C$), B ($T_g = 580\,°C$), and C ($T_g = 630\,°C$); the growth temperature for all other layers remaining fixed at 630 °C. This gave a systematic change in the mobility of back 2DEG, as diffusion of silicon is strongly temperature dependent.

By means of sequential depopulation of the double 2DEG's by the front-gate voltage, the mobility ratio between the front and back 2DEG at the same carrier concentration, $r = \mu_{front}/\mu_{back}$, was determined from the resistance at resonance and that at pinch off of the front 2DEG.[1] The values of r were approximately 2, 14, and 100 for devices A, B, and C, respectively. The symmetric-antisymmetric gap was then determined to be $\Delta_{SAS} = 1.2 \pm 0.1$ meV from Shubnikov–de Haas analysis[7] for sample A, which is in good agreement with the value of 1.3 meV calculated self-consistently.

The clearest resonant resistance enhancement was observed as a function of the back-gate voltage in sample B (Fig. 2). The resonance enhancement occurred at more negative back-gate voltages as the front-gate voltage was made more negative. This is expected as at resonance the two wells should possess equal values of carrier concentration. The figure also shows the effect of an in-plane magnetic field B_{in} which was applied perpendicular to the source-drain current. The resonant enhancement is suppressed by B_{in} as low as 1 T, because the in-plane field shifts two parabolic dispersion curves, originating from each well (see the inset of Fig. 3), and the wave functions at the Fermi level are forced to localize within each well even at the resonance condition. Systematic suppression of the resonance resistance similar to that in Fig. 2 was also observed in samples A and C. Details of this phenomena are described elsewhere.[8] Therefore, the resistance at $B_{in} = 1$ T can be regarded as the background resistance, i.e., an expected resistance when no resistance enhancement occurs. We define the size of the resistance resonance by $\Delta R/R$, where R is the resistance without resonance enhancement at the resonance gate voltage, and ΔR is the increment of the resistance due to the wave-function hybridization.

Figure 3 compares the resistance resonance as a function of front-gate voltage in three samples at a back-gate voltage of $V_{bg} = +0.6$ V; the values of $\Delta R/R$ were 0.040, 0.22, and 0.071 for devices A, B, and C. The resistance enhancement increased from A to B, as the mobility ratio was increased from 1.8 to 14. Note, however, that device C, which has the largest mobility ratio of 105, showed a smaller resonance enhancement than that of device B. This indicates that the mobility ratio is not the only factor limiting the size of the resistance resonance. It is also to be noted that the "peak," obtained by subtracting the resistance at $B_{in} = 1$ T from that at $B_{in} = 0$ T, is broadest for the device C; the full width at half maximum, ΔV_{fg}, is 0.10, 0.073, and 0.15 V for devices A, B, and C, respectively.

If the scattering rate in the back 2DEG is so large that the level broadening due to the scattering, Γ, is larger than the coupling energy Δ_{SAS}, it is expected that the symmetric and antisymmetric wave functions would not be well defined. This is because a characteristic time for the hybridization to occur is $\sim\hbar/\Delta_{SAS}$, and the lifetime

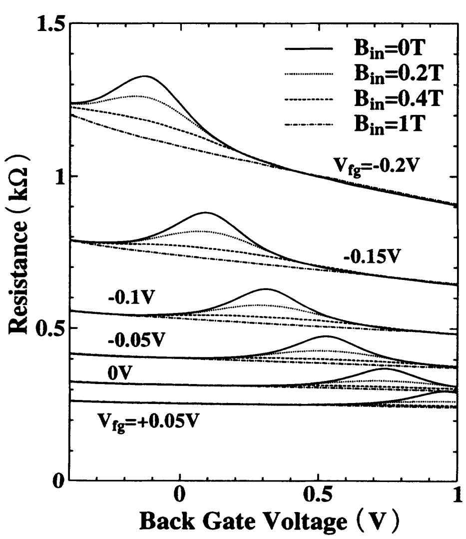

FIG. 2. Resistance as a function of the back-gate voltage at various front-gate voltages for device B, $T = 4.2$ K. The mobility ratio is ≈ 14. The resistance resonance is suppressed by an in-plane magnetic field perpendicular to the source-drain current.

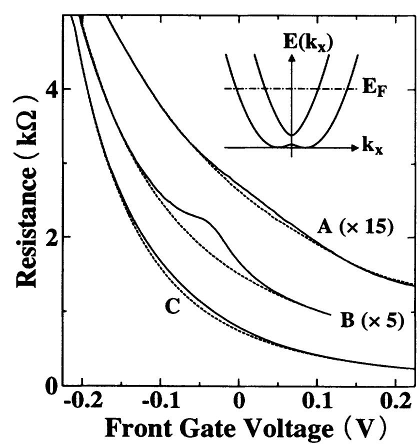

FIG. 3. Comparison of the resistance resonance among samples A, B, and C at a back-gate voltage of $+0.6$ V, $T = 4.2$ K. Solid curves, $B_{in} = 0$ T; broken curves, $B_{in} = 1$ T. The inset shows dispersion curves (energy vs wave vector) for the DQW in an in-plane magnetic field. Note that wave-function coupling occurs only near $k_x = 0$, where two energy levels anticross.

of the state is $\sim\hbar/\Gamma$. If $\Delta_{SAS} < \Gamma$, the hybridization does not take place effectively and the size of the resonance resistance will be decreased. The mobility of the back 2DEG, μ_{back}, was estimated by fully depleting the front 2DEG. For the gate bias condition shown in Fig. 3, the values of μ_{back} were 3.3×10^5, 2.6×10^4, and 1.3×10^3 for samples A, B, and C, respectively. Assuming for simplicity that the values of transport and quantum lifetimes are the same, $\mu_{back}=7.2\times10^3$ cm^2/V s corresponds to a level broadening of $\Gamma=1.2$ meV, which is the value of Δ_{SAS} of the present device structures. The back 2DEG mobility of device C is smaller than this critical value, which indicates that the level broadening is another factor in determining the size of the resistance resonance.

In a conventional theory of the resonance resistance, in which the scattering rates in the wells are additive,[1] the size of the resistance enhancement is given by a single parameter, i.e., the mobility ratio r. The conventional approach fails when $\Delta_{SAS}\approx\Gamma$ as is discussed above. Vasko has developed a quantum transport theory for DQW structures with asymmetric scattering based on a 2×2 model Hamiltonian, which is valid even when $\Gamma > \Delta_{SAS}$.[9] He assumed a short-range impurity scattering potential, and thus the transport and quantum lifetimes are identical in this theory. Using the expression given by Vasko, the size of the resistance resonance can be written as

$$[\Delta R/R]/[(r-1)^2/4r]=t^2/(1+t^2)\ , \qquad (1)$$

where $t=\Delta_{SAS}\tau/\hbar$, and $\tau^{-1}=(\tau_{front}^{-1}+\tau_{back}^{-1})/2$ is the average impurity scattering rate in the DQW. When the level broadening is small ($\hbar/2\tau \ll \Delta_{SAS}/2$), Eq. (1) reduces to an expression described in Ref. 1, namely, $\Delta R/R=(r-1)^2/4r$.

Figure 4 shows the normalized size of the resistance resonance, i.e., the left-hand side of Eq. (1), for the three samples as a function of the dimensionless parameter t, together with the theory by Vasko. Here, τ for the experimental data was estimated from the mobility, i.e., the transport lifetime. Several data points for each sample arise from the use of different back-gate voltages. The experimental error of the normalized resistance resonance is mainly from the estimate of r ($\delta r/r\approx10\%$). As is seen in the figure when the level broadening is increased (t is reduced) from sample A to C, the normalized resistance resonance decreases rapidly, which is consistent with the theory. But the discrepancy in the magnitude between theory and experiment is quite large, an order of magnitude difference for samples B and C.

It is to be noted, however, that the direct comparison between the theory and experiment is not possible, because Eq. (1) assumes that the transport and quantum lifetimes are the same. A theory of resonance resistance in which the difference in the lifetimes is incorporated is desired, since it is well known that the quantum lifetime τ_q is much smaller than transport time τ_{tr}, especially in modulation-doped heterostructures.[10,11] For example, Coleridge, Stoner, and Fletcher[10] reported $\tau_{tr}/\tau_q=3.9$ for a modulation-doped heterostructure with the mobility of $\mu=5.3\times10^4$ cm^2/V s, and $\tau_{tr}/\tau_q=8.9$ for a sample with mobility $\mu=2.4\times10^5$ cm^2/V s. If we could use τ_q rather than t_{tr} for the experimental data in Fig. 4, the value of t will be reduced and the comparison will be more favorable. Unfortunately, we could not deduce quantum lifetimes from Shubnikov–de Haas (SdH) oscillation, since the same carrier concentration exists in each well and thus the SdH oscillation consists of contributions from the high- and low-mobility 2DEG's. When the double 2DEG's exist, the contribution from the intersubband scattering will also have to be considered, which will reduce the quantum lifetime compared to that in a single 2DEG.[12,13] Inhomogeneity of the samples may also be responsible for the discrepancy. For example, monolayer fluctuations at the interfaces lead to a fairly large fluctuation of Δ_{SAS} ($\sim22\%$), when the thickness of the $Al_xGa_{1-x}As$ barrier is 25 Å. This will act as an extra scattering of the hybridized states, and will also reduce the quantum lifetime. This effect will be the same for all the samples, since the DQW's were grown at the identical growth condition. Although quantitative agreement between theory and experiment is an open question, the qualitative agreement in Fig. 4 confirms that the level broadening diminishes the resonance resistance enhancement.

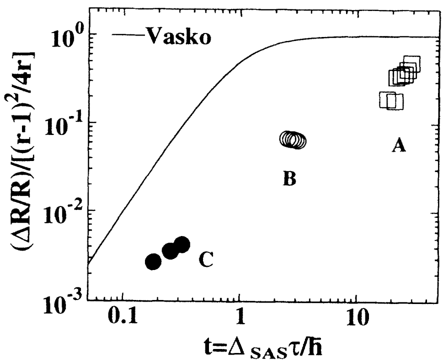

FIG. 4. Normalized size of the resistance resonance as a function of dimensionless lifetime $t=\Delta_{SAS}\tau/\hbar$ for samples A, B, and C at $T=4.2$ K. The change in t for each sample is caused by variation of the back-gate voltages. Transport lifetime was used for τ in experimental data. Solid curve was obtained from Vasko's theory (Ref. 9). $\Delta_{SAS}=1.2$ meV.

In conclusion, we have demonstrated that level broadening, as well as the mobility ratio, are key factors in understanding the phenomenon of resistance resonance.

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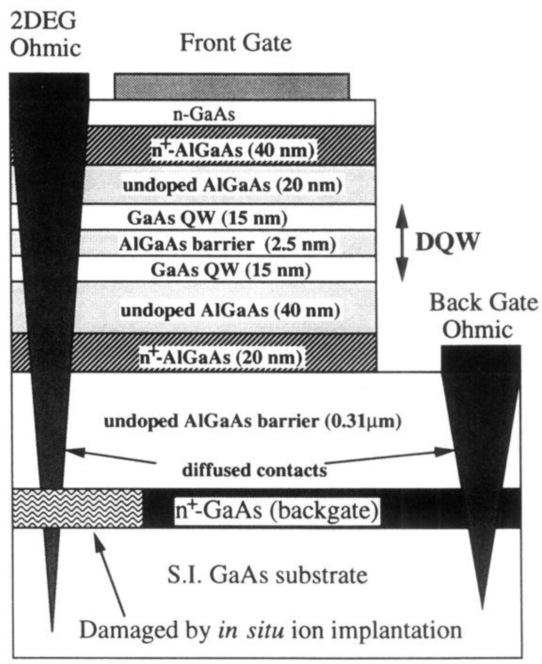

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