Parallel Magnetic Field Induced Magnetoresistance Peculiarities of the Double Quantum Well Filled with Electrons or Holes

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A magnetic field configured parallel to the quasi-2D layer, $B = B_x$, causes (i) a diamagnetic shift of the energy levels, so that the distances between them increase, and (ii) a shift along k_y of the energy dispersion surfaces $E_i(k_{||})$ [1]. The latter is interesting for a system of two coupled layers since their $E_i^{1,2}(k_{||})$ surfaces shift relative each other on $\Delta k_y^{1,2} = eBd/\hbar$, d – an effective interlayer distance [2]. A tunnel gap Δ_{SAS} existing in the energy spectrum of this double quantum well (DQW) is fixed to the intersection line of the two paraboloids. The upper edge of Δ_{SAS} corresponds to a minimum $E_m(k_{||})$ of the inner surface in this joint energy dispersion, and the lower edge – to a saddle point on the external surface. The gap lifts in energy as the paraboloids move away from each other with increasing field.

If the zero-field Fermi level position is above the gap, the $E_m(k_{||})$ would cross the Fermi level at a field B_m, and then a saddle point cross it at a field $B_s > B_m$. At $B > B_m$ the density of states (DOS) drops down and the intersubband scattering is quenched resulting in a down step or a minimum in magnetoresistivity (MR) $\rho\ (B_{||})$ at $B \approx B_m$. Also, a van Hove divergence in DOS is connected with the saddle point causing a MR maximum at $B \approx B_s$. Peculiarities of both types have been found in DQW created in the conduction band of the traditional GaAs/*n*-AlGaAs heterosystem [3-5].

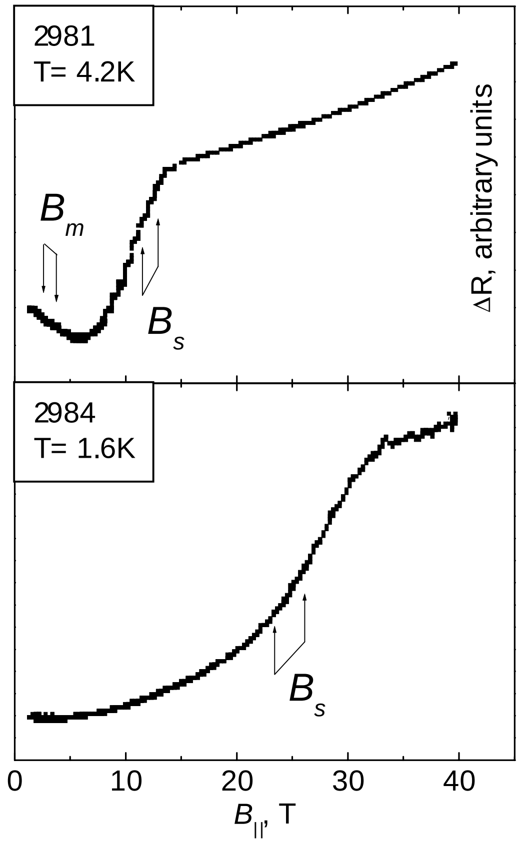

Fig.1. MR of the InGaAs/*n*-GaAs DQWs.

In this paper we report on investigations of the DQWs under parallel magnetic fields in materials other than GaAs/*n*-AlGaAs. First, we present results for $In_xGa_{1-x}As$/*n*-GaAs DQW containing the electron gas. At least one new property is important here – a significant spin splitting of the conduction band due to large *g*-factor of the InAs component, while this is negligible in GaAs. Second are the results for Ge/*p*-$Ge_{1-x}Si_x$ DQW containing a *hole* gas. A novel situation emerges in the valence band DQW due to a mixing of the heavy and light hole states.

$In_{0.18}Ga_{0.82}As$/*n*-GaAs DQWs consist of 5 nm wide wells and GaAs barriers symmetrically doped with 19 nm empty spacers on both sides of DQW. Two samples have been studied: 2981(2984) with the barrier width of 7(3.5) nm, electron gas density $n_s = 2.05(2.34)\cdot 10^{15}$ m^{-2} and low-temperature mobility of 2.6(1.6) m^2/V·s. A rich quantum Hall (QH) structure present for both samples in perpendicular fields. Results in parallel fields are depicted in fig.1. The tunnel gap was determined from self-consistent calculations of the Schrodinger and Poison equations for zero magnetic field: $\Delta_{SAS} = 7.4(23.1)$ meV and the Fermi level $E_F = 8(9.5)$ meV. Since $E_F > \Delta_{SAS}$ in sample 2981, both a minimum and a maximum exist in its

MR. Contrary, $E_F << \Delta_{SAS}$ in sample 2984, and only a maximum exists at $B \approx 30$ T. Shown in fig.1 are the B_m and B_s positions as calculated from the tight binding approximation [5]. While the difference in the structure of MR for these two samples is understandable, the calculated peculiarity positions are lower than the experimental ones. Possible reasons of deviations could be as follows. First, the spin splittings in fig.1 are presented for zero-field value of $|g| = 3$ interpolated for $In_{0.18}Ga_{0.82}As$. It may become considerably larger as the electron gas become spin-polarized [6], and the calculated high-field spin-splitted components of the peculiarities would approach those experimental. Second, a correct self-consistent consideration of the electron gas redistribution across the layer under parallel field [5] may yield the B_s positions shifted to higher fields.

We have found some local peculiarities in the parallel magnetic field MR for the Ge/*p*-GeSi heterostructures containing the *hole* gas in a self-formed DQW within a Ge layer (samples 475/476 in fig.2). The DQW potential profile emerges in a Ge layer wider than $d_w \approx 30$ nm at hole densities above $p_s \approx 1 \cdot 10^{15}$ m^{-2}, that manifests in the disappearance of the QH plateaus for filling factor $\nu = 1$ [7]. The MR traces for samples of the same heterosystem but with more narrow Ge layers (~20 nm, samples 1123 and 1125 in fig.2), for which the DQW profile has not formed yet, are smooth. Thus it is tempting to explain the peculiarities in the wide layer samples in analogy with those observed in the DQW with electron gas. But our calculations indicate that the tunnel gap here is very narrow, $\Delta_{SAS} \sim 0.1$ meV, due to high hole mass. The magnetic field interval for such a narrow Δ_{SAS} is about 0.1 T, an order of magnitude smaller than those observed experimentally.

In a parallel magnetic field the samples with a self-formed DQW reveal a strong negative MR similar to that observed in samples 1123 and 1125. The obvious cause for the negative MR in the latter samples is a depopulation of the second subband due to its diamagnetic shift. In samples 475/476 the two lower subbands merge in the DQW energy profile, but the *third* subband may be populated if the hole mass in the lower subbands is essentially different in directions perpendicular and parallel to the layer: $m_\perp/m_{||} > \sim 5$. This condition is feasible for the valence band due to mixing of the heavy and light hole states [8], and low values for $m_{||}$ are indeed determined from the temperature damping of the Shubnikov – de Haas oscillations. Thus the negative MR in samples 475/476 is also due to the depopulation of the upper subband. The upper hole subbands have a complicated structure with lateral extrema at $k_{||} \neq 0$ [8], and our calculations reveal that in a wide well of finite depth these lateral extrema deepen due to small distances between the heavy and light hole levels. In this case the observed local peculiarities in ρ ($B_{||}$) are due to this complicated subband structure, and the Fermi level scans it while going out from the third subband.

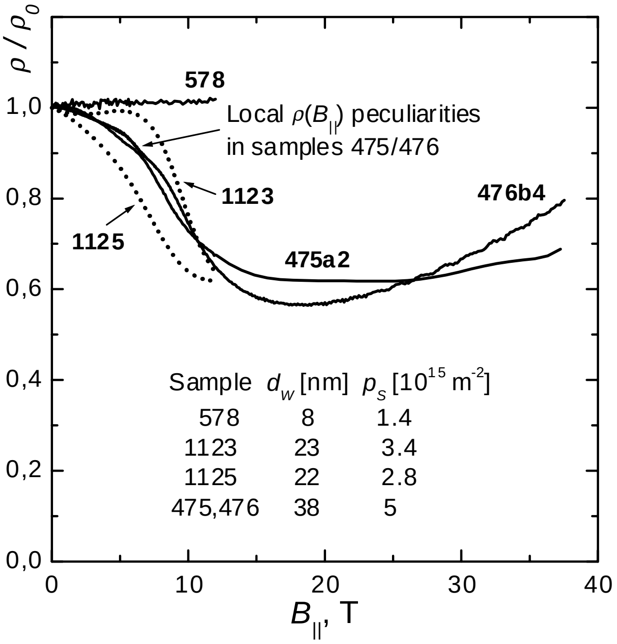

Fig.2. Magnetoresistance of Ge/*p*-GeSi samples.

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