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(120)-ORIENTED CdTe/CdMnTe QUANTUM WELL STRUCTURES GROWN BY MOLECULAR BEAM EPITAXY*

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We report on the MBE growth and magnetooptical studies of (120)-oriented CdTe/CdMnTe quantum well structures. The quality of structures, as evaluated by the photoluminescence line width, was as good as that of the best structures grown in ⟨100⟩ direction. No spin splitting enhancement, expected theoretically, due to the reduction of the antiferromagnetic interaction between Mn ions in CdTe/CdMnTe digital alloy quantum wells grown along ⟨120⟩ direction was observed.

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Diluted magnetic semiconductors (DMS) (e.g., $Cd_{1-x}Mn_xTe$) exhibit many interesting properties of which a giant spin splitting of conduction electrons and valence band holes is the most spectacular [1]. The giant spin splitting is proportional to the magnetization and, thus, at low Mn concentrations it is proportional to the Mn molar fraction x. For sufficiently large values of x, a considerable fraction of Mn ions form antiferromagnetically coupled nearest neighbor pairs (or larger clusters) which do not contribute to the magnetization in weak magnetic fields (weak compared to nearest neighbor Mn–Mn spin coupling strength). As a consequence, the magnetization as a function of x (at a constant magnetic field and temperature) passes through a maximum at about $x = 0.13$ and shows a decreasing trend for larger x values. This fact sets an upper limit for the magnitude of the giant spin splitting attainable in DMSs in weak fields.

One of the possible ways out of this limitation involved an idea of a very short period MnTe/CdTe superlattice (digital magnetic superlattice) — with the period as short as only four monolayers (ML), i.e., 1 ML MnTe alternating with 3 ML of CdTe — with the growth axis parallel to ⟨120⟩ crystallographic direction [2]. In such a configuration, the closest Mn ions are always in the second nearest neighbor positions of the fcc lattice (i.e., by a factor of $\sqrt{2}$ further apart than

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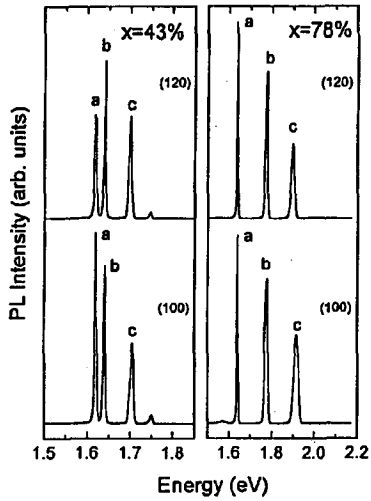

Fig. 1. PL spectra of two pairs of simultaneously grown (100)- and (120)-oriented quantum well structures taken at $T = 10$ K. Each structure contains three QWs: two regular CdTe QWs with the width 77.8 Å and 19.5 Å labeled *a* and *c*, respectively, and one DMQW (3×1) labeled *b*. Compositions of the barriers are given in the figure.

the nearest neighbors) with the exchange interaction constant being by an order of magnitude smaller. This should lead to an increase in the magnetization and, thus, in the giant spin splitting of the resultant $Cd_{0.75}Mn_{0.25}Te$ material.

We attempted to achieve such a material by molecular beam epitaxy (MBE) to which end conditions of growth on (120) low symmetry surface of a substrate had to be first established. Growth processes were performed in the EPI 620 MBE system using standard MBE growth mode. High quality (120) CdTe substrates were fabricated at the Institute of Physics of the Polish Academy of Sciences.

First, standard CdTe quantum wells with $Cd_{1-x}Mn_xTe$ barriers were grown along the ⟨120⟩ direction. Metal rich conditions of growth were employed, with CdTe and Cd effusion cells continuously opened for the growth of the wells, and with CdTe, Cd and Mn shutters continuously opened for the growth of the barriers. We found that the beam equivalent pressure ratio of Cd to Te fluxes equal to 1.5 — optimum for the growth on (100) substrates — is also appropriate for the growth of quantum wells (QWs) in ⟨120⟩ direction. A good quality of the new structures was proved by studies of low-temperature photoluminescence (PL). The PL line width of (120)-oriented CdTe/CdMnTe quantum wells was as narrow as in our best structures grown along ⟨100⟩ direction. This can be clearly seen in Fig. 1, showing PL of multiple QW structures grown simultaneously on (100)- and (120)-oriented substrates. Since we were not able to observe reflection high-energy electron diffraction (RHEED) intensity oscillations for the growth along the ⟨120⟩ direction, the growth rates were determined by measuring the period of the oscillations observed for the (100)-oriented sample grown simultaneously. It can be seen in Fig. 1 that the energy position of the PL peak for the 19.5 Å wide QW grown

along the ⟨100⟩ direction is close to its position in the respective ⟨120⟩-oriented QW. Therefore, assuming an isotropic effective mass in CdTe, the growth rates in both directions should be very similar.

Next, we fabricated a series of digital magnetic quantum wells (DMQW) [3] — that is QWs in which the well material was made of a digital magnetic superlattice — with different average Mn composition. The barriers in these structures were made of a regular (i.e., non-digital) $Cd_{1-x}Mn_xTe$ mixed crystal. For the purpose of a precise comparison, we simultaneously grew samples on both (100)- and (120)-oriented substrates. Two sets of DMQWs were fabricated. In the first set the well material was composed of three monolayers of CdTe (assuming ⟨120⟩ interlayer distance) alternated with a single monolayer of $Cd_{1-x}Mn_xTe$ (CdTe [3 ML]×$Cd_{1-x}Mn_xTe$ [1 ML], denoted as (3×1)). The barrier composition in this series was varied and was equal to 0.10, 0.43, 0.78 in different samples (see Fig. 1). In the second series the same barrier composition $x = 0.78$ was used while the wells were built of (3×1), (4×1), (5×1) and (6×1) digital magnetic superlattices, respectively. These two series should, in principle, allow to find enhanced spin splitting in spite of uncertainty of growth rate and a finite interdiffusion at interfaces. In order to minimize the latter effect, the substrate temperature was reduced for the second set of structures from 320 to 270°C, as estimated from a thermocouple readout.

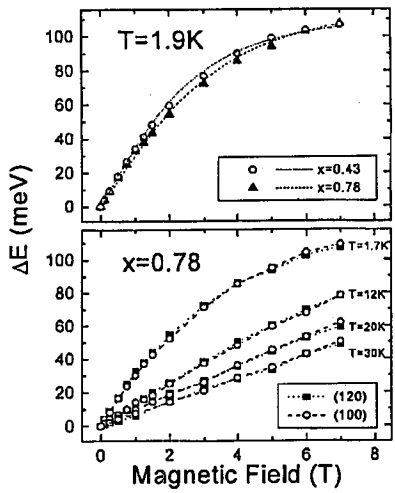

Fig. 2. Heavy hole hh_1–e_1 exciton spin splitting as a function of a magnetic field. Upper panel shows the splitting for two (3×1) DMQWs with the barrier compositions $x = 0.43$ and $x = 0.78$ (points), corresponding to the average compositions of the digital alloy $x = 0.11$ and $x = 0.19$, respectively. The lines represent the calculated spin splitting in the bulk mixed crystal with the composition equal to the average composition of the digital alloy. Lower part shows a comparison of the spin splitting for (100)- and (120)-oriented samples, grown simultaneously, collected at different temperatures between 1.7 and 30 K. The lines are to guide the eye.

Magnetoreflectivity of these samples was measured in magnetic fields up to 7 T and at temperatures ranging from 1.9 to 30 K. Experiments were performed in the Faraday configuration in two circular polarizations. The analysis of the spectra yielded the spin splitting of the heavy hole (hh_1–e_1) excitons. Typical results are presented in the upper part of Fig. 2.

Surprisingly, the spin splitting of hh_1–e_1 excitons in (120)-oriented samples did not differ from that in DMQW grown along ⟨100⟩ direction in the entire range of the magnetic field and the temperature (see Fig. 2, lower part). Moreover, the splitting can also be correctly reproduced assuming a value of magnetization suitable for the bulk material [4]. One of the possible explanations is that the growth on (120) surface did not proceed in the exactly layer-by-layer mode, although optical quality of QWs was very good. The fact that there were no RHEED intensity oscillation observable for this growth orientation is in agreement with the above interpretation. If this is in fact the reason for us observing no changes in the spin splitting, then the atomic layer epitaxy may be a method of achieving the layer-by-layer growth mode on (120)-oriented substrates. More experiments are necessary to clarify the problem.

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