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From weak to strong localization in a ferromagnetic high mobility 2DHG

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ABSTRACT

Manganese modulation-doped two-dimensional hole systems confined in strained InAs/InGaAs/InAlAs heterostructures were investigated by low-temperature magnetotransport experiments. The study demonstrates quantized transport phenomena in the high field region, weak anti-localization in the low-field region and ferromagnetic ordering in the separated and insulating manganese-doped layer. A significant amount of manganese in the channel of inverted modulation-doped structures causes a strong localization effect with hysteretic-like abrupt resistance changes over several orders of magnitude at very low temperatures.

Low-dimensional charge carrier systems confined in InGaAs or InAs quantum wells (QWs) hold advantageous properties such as large *g*-factor and significant spin-orbit coupling [1,2] to study spin-dependent transport phenomena in reduced dimensions. Diluted magnetic semiconductors highly doped with manganese (Mn) feature hole-mediated ferromagnetism [3]. For high doping concentration ($>2\%$) metallic behavior is achieved resulting in poor charger carrier mobility and short mean free path of only a few lattice constants [4]. Combining InAs-based heterostructures together with Mn modulation doping afford to explore the interaction of spins of highly mobile two-dimensional holes with magnetic moments of 5/2 provided by Mn ions.

Therefore we have investigated ferromagnetic Mn modulation-doped two-dimensional hole gases (2DHGs) with low-temperature magnetotransport experiments. The samples were grown on strain-relaxed metamorphic buffers on semi-insulating (0 0 1) GaAs substrate by means of molecular beam epitaxy. The active layer consists of a 20 nm InGaAs QW with an inserted 4 nm InAs channel and a 7-nm-thick Mn-doped InAlAs layer that is 5 nm separated from the QW. The Mn acceptor concentration in the InAlAs doping layer is less than $2\times10^{20}\,cm^{-3}$ as estimated from flux calibration of the Mn effusion cell [5]. The In concentration in the active region amounts to 75% leading to a compressive strain in the InAs channel hosting the 2DHG. Magnetotransport measurements were performed on optically defined and wet chemical etched Hall bars aligned along the [1 1 0] crystallographic direction using standard four-terminal low-frequency lock-in technique with an excitation current of $I=100\,nA$ for resistance values less than 30 K. High resistance states were quantified in a two-terminal geometry applying a constant excitation voltage $U_{bias}=0.5\,V$ and measuring the flowing current through the device. The resistance is then calculated by $R=U_{bias}/I$.

The difference of the two QW structures of interest in this paper is the position of the doping layer with respect to the growth direction. Schemes of the QW layer sequence are inserted in Fig. 1. In the normal structure (Fig. 1(a)) the Mn-doping layer is carried out after the InGaAs/InAs QW growth and in the inverted structure (Fig. 1(b)) the doping layer is grown before the QW. Asymmetric broadening of the doping layer causes a significant amount of Mn in the InAs channel of the inverted structure. This has been quantified by secondary ion mass spectroscopy (SIMS) measurements to about 1% of the Mn concentration in doping layer, whereas the quantum well region of the normal structure is free of Mn [5].

As demonstrated in Fig. 1, low-temperature magnetotransport measurements on both structures in the four-terminal geometry at $T=200$ mK reveal clear Shubnikov-de Haas (SdH) oscillations in the longitudinal resistance R_{xx} and quantum Hall plateaus in the transverse resistance R_{xy}. The positive Hall coefficient proves the transport in a hole systems and the vanishing longitudinal resistance at lower filling factors excludes the existence of a parallel conducting channel. The two-dimensional hole density p was ascertained from the classical Hall slope and confirmed from the $1/B$ periodicity of the SdH oscillations and constitutes $p=4.3\times10^{11}\,cm^{-2}$ and $p=4.4\times10^{11}\,cm^{-2}$ for the normal and inverted doped structure, respectively. The more pronounced SdH oscillations and quantum Hall plateaus reveal a higher mobility for the normal compared to the inverted doped structure. Substantial differences are visible in the low-field region. A

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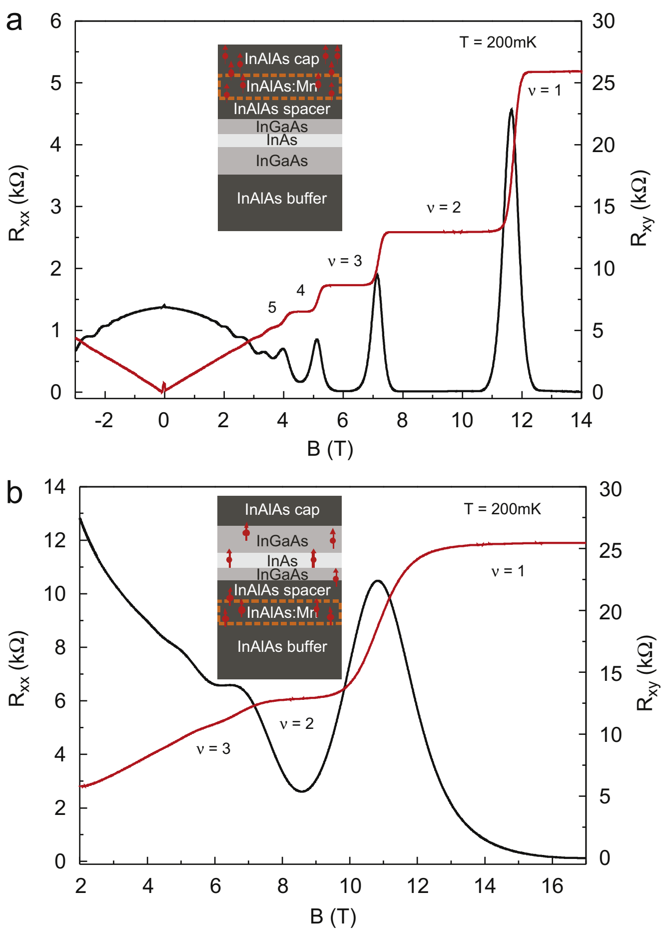

Fig. 1. (a) Longitudinal resistance R_{xx} (black) and Hall resistance R_{xy} (red) at T=200 mK for normal (a) and inverted (b) Mn modulation-doped QW structure reveal clear Shubnikov-de Haas oscillations with vanishing resistance at lower filling factors and quantum Hall plateaus. Inset in (a), (b), schematic layer sequence of the normal and inverted doped QW structures consisting of an InGaAs layer with an asymmetric embedded strained InAs channel in InAlAs barriers. In contrast to the normal doped QW (a), the low-field resistance of the inverted structure (b) increases strongly in the low-field region (only shown down to B=2 T). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

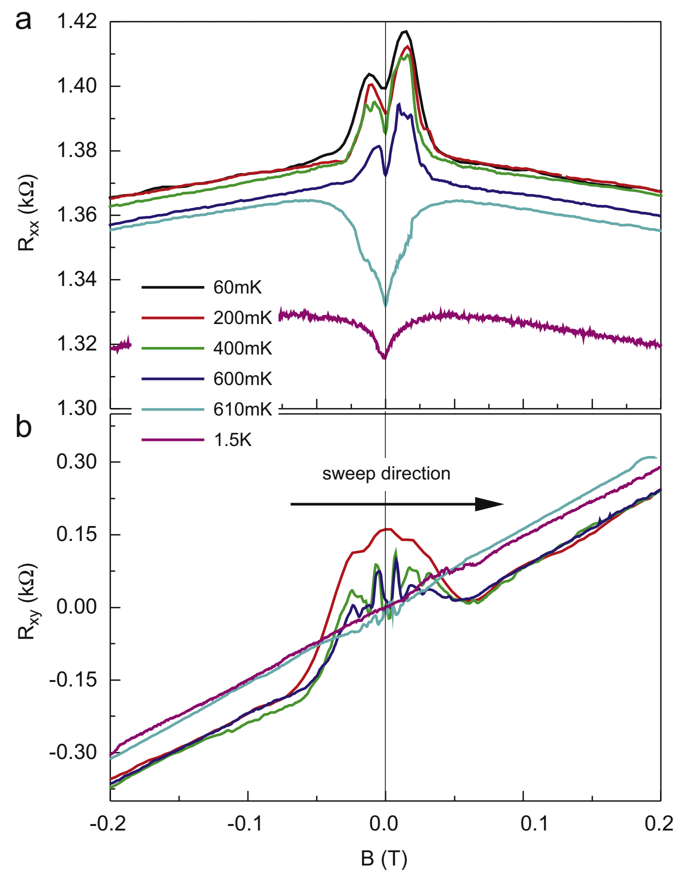

Fig. 2. Longitudinal magnetoresistance R_{xx} (a) and Hall resistance R_{xy} (b) in the vicinity of B=0 T for temperatures ranging from T=50 mK to T=1.5 K for the normal doped QW without Mn in the channel. (a) The sign of R_{xx} changes between T=610 mK (cyan) and T=600 mK (blue) from weak anti-localization like behavior to a hysteretic-like rise with a minimum at B=0 T. (b) The Hall resistance traces R_{xy} show for $T \leq 600$ mK an additional feature around B=0 T and are shifted vertically compared to the traces for $T > 600$ mK.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

moderate parabolic background (Fig. 1(a)) that can be explained by electron–electron interaction and weak anti-localization (WAL) behavior in the vicinity of B=0 T (Fig. 2(a)) appears in the longitudinal magnetoresistance traces R_{xx} of the normal doped sample [6], whereas a huge increase in R_{xx} of the inverted doped sample is detectable (Fig. 1(b)). For this reason, the magnetoresistance of the inverted structure in Fig. 1(b) is plotted only above B=2 T. We ascribe this giant negative magnetoresistance to strong localization of the itinerant holes on the localized magnetic moments of 5/2 provided by the Mn ions in or close to the channel [5,7,8].

In Fig. 2 we focus on the low-field properties of the normal doped QW for temperatures ranging from T=50 mK to T=1.5 K. The magnetic field was always swept from negative to positive field values as indicated by an arrow in Fig. 2(b). In R_{xx} (WAL) behavior in the traces from T=1.5 K to T=610 mK is indicated by the minima exact at B=0 T and demonstrating strong spin-orbit coupling as also known for non-magnetic two-dimensional electron systems in InAs heterostructures [1,2]. A reproducible sharp transition within 10 mK from WAL to a hysteretic double-maxima behavior occurs that can be interpreted as phase transition from a paramagnetic to a ferromagnetic state. Due to the fact that the minima in R_{xx} for $T \leq 600$ mK appears exactly at B=0 T we interpret the longitudinal resistance signal in the ferromagnetic phase as a superposition of hysteretic anisotropic magnetoresistance and WAL. Precise analysis of the transverse magnetoresistance signal substantiates this assumption. As depicted in Fig. 2b) the signal in R_{xy} also changes exactly between T=600 mK and T=610 mK. The weak temperature dependence and deviation from the classical Hall slope corresponding to the two-dimensional hole density p for $T \geq 610$ mK can be attributed to a contribution of the anomalous Hall effect to R_{xy} in the paramagnetic phase. For $T \leq 610$ mK a superposition of normal, anomalous and temperature-dependent and hysteretic planar Hall effect is observable. The existence of planar Hall effect provides evidence for a spontaneous magnetization with a component parallel to the QW. This is in good agreement to the explanation of the features in R_{xx} by superposition of anisotropic magnetoresistance and WAL. The magnetic ordering seems to occur in the Mn-doped InAlAs layer, because the QW is free of Mn in this structure [6]. Coexistence of insulating behavior and hole-mediated ferromagnetism in very low Mn-doped III-As hetero-structures is feasible as demonstrated in Ref. [9].

In the low-field region of the inverted sample hysteretic behavior with abrupt resistance changes over several orders of

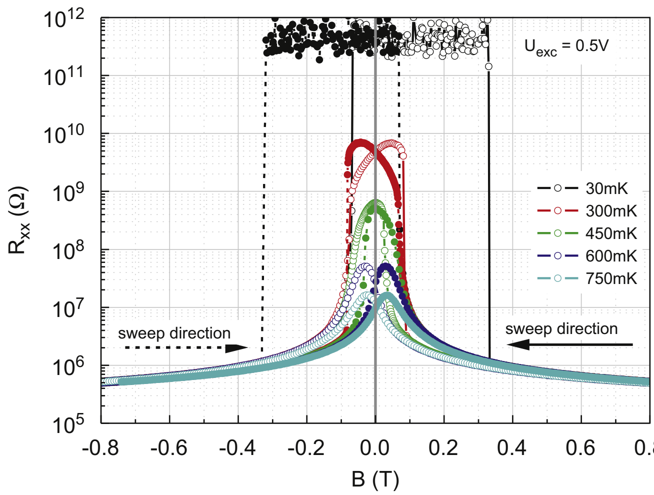

Fig. 3. The two-terminal resistance in the low-field region of the inverted doped structure shows temperature-dependent hysteresis and abrupt resistance drops over more than 5 orders of magnitude at the lowest temperature T=30 mK (black). The absolute resistance values and the jump-field are strongly temperature dependent. The jumps in the resistance disappear for $T>400$ mK and the hysteresis is still visible at T=600 mK. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

magnitude can be observed by applying a perpendicular magnetic field as exhibited in Fig. 3. The two-terminal resistance exceeds $R_{xx,\ 2\text{-term}}>10^{11}$ for T=50 mK representing only the upper limit of the set-up. Both, the maximum resistance value and the critical magnetic field value for which the abrupt insulator-to-metal transition appears are strongly temperature dependent, whereas the transition from the conducting to the insulating state with decreasing magnetic field is smoother and the critical field is barely temperature dependent. The resistance drops disappear above 600 mK and the hysteresis above 750 mK. The absence of a clear phase transition temperature together with disappearance of resistance jumps and hysteresis at unequal temperatures seems to exclude ferromagnetic ordering in the channel to be responsible for the shown striking features at the inverted QW structure. The very low Mn concentration less than 2×10^{18} cm^{-3} ($<0.01\%$) substantiates this assumption. The abrupt and giant resistance changes are apparently induced by localization of the itinerant holes on magnetic ions in the vicinity of the 2DHG. Coexistence of magnetic ordering in the higher Mn-doped insulating InAlAs layer is feasible.

In summary, our magnetotransport data on Mn modulation-doped InAs QW structures demonstrate the existence of a high-quality 2DHGs with quantized transport phenomena in the high field region without a parallel conducting channel, e.g. the highly Mn-doped InAlAs layer. Broadening of the Mn atoms during the MBE growth involves Mn impurities in the channel for all inverted doped structures leading to hysteretic abrupt resistance changes over several orders of magnitude with an highly insulating state in the low-field region at millikelvin temperatures. Investigations of a normal doped structure without Mn ions close to the QW feature a distinct phase transition within 10 mK from paramagnetism to ferromagnetism verified by hysteretic anisotropic magnetoresistance and planar Hall effect in R_{xx} and R_{xy}, respectively. WAL behavior was found for the normal doped layer in a large temperature range as well as in the ferromagnetic phase indicating strong spin-orbit coupling. The hole-mediated ferromagnetism is induced in the insulating and spaced InAlAs layer by the inserted Mn ions and should be present in both structures independent from the position of the doping. The metal-insulator transition with the intriguing features in the insulating phase seems to be independent from the magnetic ordering in the InAlAs:Mn layer. No clear evidence of magnetic ordering in the channel hosting the 2DHG was found experimentally.

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