Current heating of a magnetic two-dimensional electron gas in $Hg_{1-x}Mn_xTe/Hg_{0.3}Cd_{0.7}Te$ quantum wells

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(Received 11 December 2003; revised manuscript received 15 April 2004; published 18 November 2004)

Heating caused by electrons with excess kinetic energy has been investigated in a magnetic two-dimensional electron gas in $Hg_{1-x}Mn_xTe/Hg_{0.3}Cd_{0.7}Te(001)$ quantum wells. The temperature of the Mn ions T_{Mn} has been determined by the node positions in the beating pattern in Shubnikov–de Haas oscillations. The experimental dependence of T_{Mn} on current and therefore on electron temperature, is in excellent agreement with a rate equation model.

DOI: 10.1103/PhysRevB.70.195328 PACS number(s): 73.50.Gr, 73.61.Ga, 73.63.Hs

I. INTRODUCTION

In the recently introduced magnetic two-dimensional electron gas (M2DEG)[1] magnetic ions (usually Mn ions) are exchange coupled to the 2DEG. Spin interactions[2] and spin dependent transport and localization[1] have been investigated in these systems. The Mn ions induce a giant Zeeman splitting of the electron states, which results in a pronounced beating in the Shubnikov–de Haas (SdH) oscillations.[3,4] In a narrow gap M2DEG in $Hg_{1-x}Mn_xTe$ quantum wells (QW's) with an inverted band structure, Rashba, Zeeman, and Landau effects have been shown to be of comparable magnitude.[5] In this material system, the giant Zeeman splitting caused by the *sp-d* exchange interaction can be efficiently suppressed by increasing the manganese temperature, while the spin-orbit (SO) splitting only depends on the asymmetry[6] of the QW and is not sensitive to temperature.[5,7] The band structure of this system, which has been determined by means of optical[8] and magnetotransport[9] experiments combined with self-consistent $\boldsymbol{k}\cdot\boldsymbol{p}$ calculations, is distinguished by a first conduction subband ($H1$) with heavy hole character and consequently a large SO splitting.[5,9]

Recently, Keller *et al.*[10] have found an efficient energy transfer from the photoexcited carriers to the Mn system, which raised the temperature of the magnetic ion system in a $Zn_{1-x}Mn_xSe/Zn_{1-y}Be_ySe$ M2DEG. However, the power of the laser radiation is much higher than that of the current normally employed in a magnetotransport experiment. Thus a comparison of these two methods is of interest. In this article, we report on the current heating of the 2DEG and the Mn ion system in $Hg_{1-x}Mn_xTe/Hg_{0.3}Cd_{0.7}Te(001)$ QW's. Samples with different Mn concentrations have been studied as a function of current by means of their SdH oscillations in the resistivity ρ_{xx}. It has been found that relatively small current densities cause a strong suppression of the giant Zeeman splitting of the conduction electrons, and this effect is strongly dependent on the Mn content.

II. EXPERIMENTAL DETAILS

A series of *n* type $Hg_{1-x}Mn_xTe/Hg_{0.3}Cd_{0.7}Te(001)$ QW's were grown by molecular beam epitaxy on $Cd_{0.96}Zn_{0.04}Te(001)$ substrates. The QW's were modulation doped using CdI_2 as a doping material. The $Hg_{1-x}Mn_xTe$ well width is 12 nm and the $Hg_{0.3}Cd_{0.7}Te$ barriers consist of a 5.5 nm thick spacer and a 9 nm thick doped layer. The Mn concentration x of the $Hg_{1-x}Mn_xTe$ well was determined by means of energy dispersive x-ray fluorescence (EDAX) on thick epitaxial layers of $Hg_{1-x}Mn_xTe$. This was done for a series of x values in order to improve the accuracy.

Standard Hall bars with a width of 200 μm were fabricated by wet chemical etching. A 200 nm thick Al_2O_3 film was deposited on top of the structure, which serves as an insulating layer, and Al was evaporated to form a metallic gate on top of this layer. Ohmic indium contacts were fabricated by thermal bonding. Magnetotransport measurements were carried out using dc techniques with currents of 1 μA to 1.2 mA in magnetic fields ranging up to 7 T and bath temperatures down to 1.4 K. The carrier concentrations and the Hall mobilities were determined to be 3.3×10^{12} cm^{-2} and 5.2×10^4 cm^2/V s for Q1697 ($x=0.015$), and 4.2×10^{12} cm^{-2} and 2.0×10^4 cm^2/V s for Q1715 ($x=0.064$) at 4.2 K for zero gate voltage from low magnetic field Hall measurements.

III. RESULTS AND DISCUSSION

Figures 1 and 2 show a distinct beating pattern in the SdH oscillations of samples Q1697 ($x=0.015$) and Q1715 ($x=0.064$) for various currents at 1.4 K. Nodes in the beating pattern shift with current but can no longer be resolved when the current exceeds 1 mA. These nodes correspond to the equivalence of the spin splitting energy and that of a half integer multiple of the Landau splitting energy. In our $Hg_{1-x}Mn_xTe/Hg_{0.3}Cd_{0.7}Te$ samples, the total spin splitting energy is a combination of Rashba[11] SO and giant Zeeman splitting energies.[5] The Rashba SO effect is due to the structure inversion asymmetry of the quantum well. However the Rashba effect does not depend on temperature,[7] and consequently does not influence the results. Only currents were employed which did not change the 2DEG concentration and therefore the asymmetry of the QW, i.e., $\leqslant 400$ μA and $\leqslant 1.2$ mA for Q1697 and Q1715, respectively.

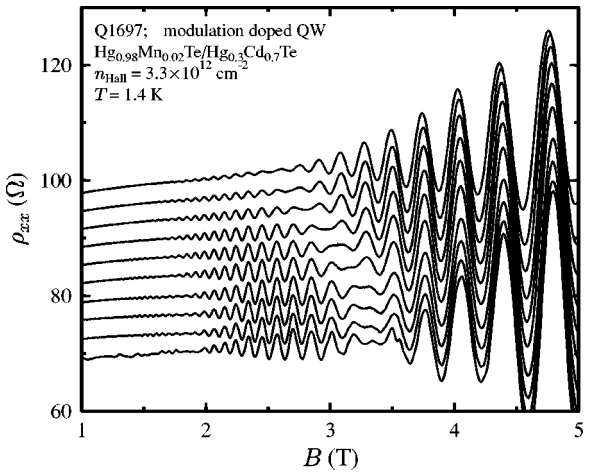

FIG. 1. SdH oscillations at various currents for sample Q1697 ($x=0.015$) at a lattice temperature T_L of 1.4 K. The curves from bottom to top corresponded to the currents of 1, 10, 20, 50, 75, 100, 150, 200, 300, and 400 μA, respectively. The plots are offset 2 Ω for clarity.

Only giant Zeeman splitting depends on the temperature of the Mn ions T_{Mn} according to the phenomenological expression[12–14]

$$E_Z = g_0\mu_B B - (\Delta E)_{\max} B_{5/2}\left[\frac{(5g_{\mathrm{Mn}}\mu_B B)}{2k_B(T_{\mathrm{Mn}}+T_0)}\right], \qquad (1)$$

where $g_{\mathrm{Mn}}=2$, μ_B is the Bohr magneton, B is the magnetic field, and g_0 is the g factor for a HgTe QW without Mn,[15] i.e., $g_0=-20$. $B_{5/2}(x)$ is the Brillouin function for a spin of $S=5/2$, empirically modified by using a rescaled temperature $T_{\mathrm{Mn}}+T_0$ to account for antiferromagnetic spin-spin interaction, and $(\Delta E)_{\max}$ is the saturated splitting energy caused by *sp-d* exchange interaction. If $(\Delta E)_{\max}$ and T_0 are known, then this modified Brillouin function can be used to determine the T_{Mn}. To accomplish this the nodes in SdH oscillations at known lattice temperatures and a current of 1 μA were analyzed, see, for example, Fig. 3. The resulting values of $(\Delta E)_{\max}$ and T_0 for Q1697 and Q1715 together with other experimental and semiempirical values for T_0 from a magnetic susceptibility study of $Hg_{1-x}Mn_xTe$ alloys,[16] are listed in Table I. Obviously the experimental values of T_0 are in good agreement with those of Bastard and Lewiner.[16]

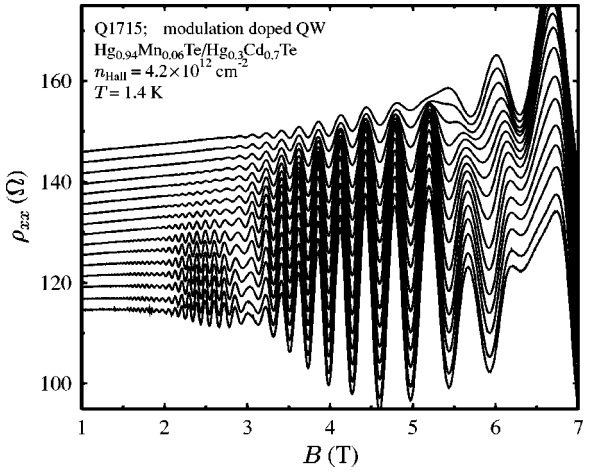

FIG. 2. SdH oscillations at various currents for sample Q1715 ($x=0.064$) at $T_L=1.4$ K. The curves from bottom to top corresponded to the currents of 5, 10, 20, 50, 75, 100, 150, 200, 300, 400, 500, 600, 800, 1000, and 1200 μA, respectively. The plots are offset 2 Ω for clarity.

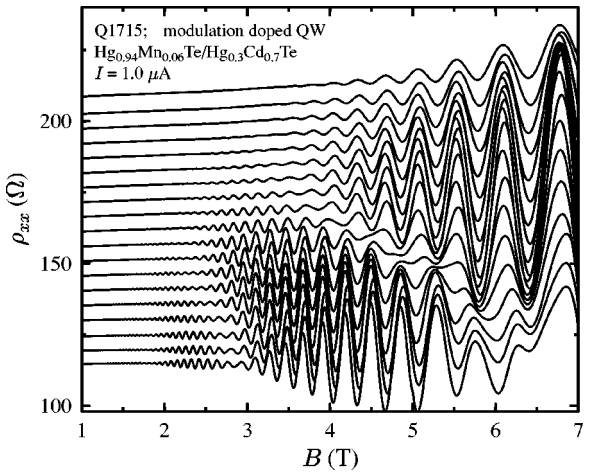

FIG. 3. SdH oscillations for Q1715 ($x=0.064$) at temperatures of 1.4, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10, 12, 14, 16, 18, 20, 23, 26, 31, and 41 K from bottom to top. The plots are offset 5 Ω for clarity.

Hence, T_{Mn} for the current heating experiment can be determined via Eq. (1). Finally, the temperature of the hot electrons has been determined from the temperature dependence of the amplitudes $A(T_e)$ of the fast Fourier transformation of the SdH oscillations,[17] which scales as follows:

$$A(T_e) = \frac{X}{\sinh(X)}, \qquad (2)$$

where

$$X = 2\pi^2\frac{k_B T_e}{\hbar\omega_c} \qquad (3)$$

and the electron effective mass m^* is 0.054 m_0 and 0.051 m_0 for Q1697 and Q1715, respectively.

The results for T_e and T_{Mn} are shown for Q1715 in Fig. 4 as a function of current squared I^2. The increase in electron temperature is proportional to I^2 at low current values up to about 100 μA. The energy relaxation time associated with

TABLE I. Experimental values for $(\Delta E)_{\max}$ and T_0 from this work and experimental (a) and semiempirical (b) values after Bastard and Lewiner (Ref. 16).

	x	$(\Delta E)_{\max}$ meV	T_0 K	(a) T_0^{exp} K	(b) T_0^{th} K
Q1697	0.015	4.5±0.5	2.5±0.5	3.0	3.3
Q1715	0.064	24±4	5±1		5.6

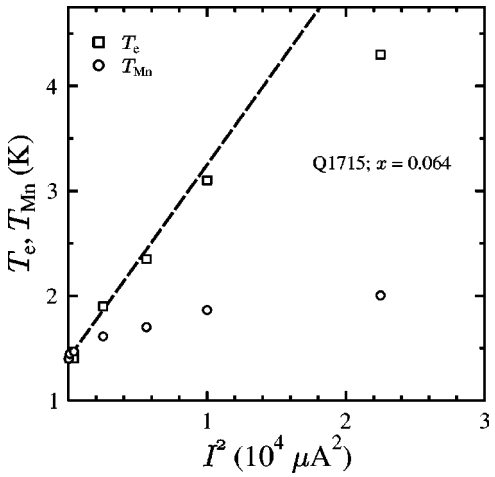

FIG. 4. Temperature of the electrons and Mn ions in Q1715 ($x=0.064$) versus current squared. The straight dashed line represents the slope of $T_e(I^2)$ at low currents.

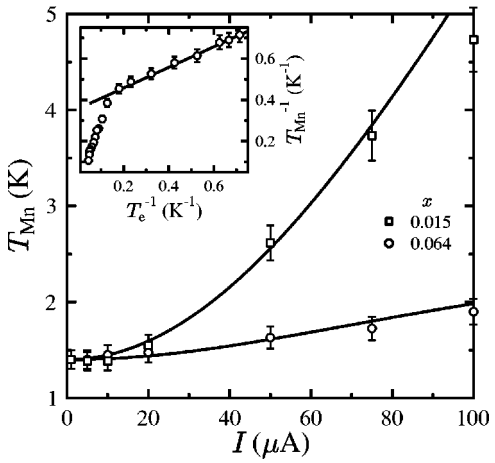

FIG. 5. The Mn temperature versus current for Q1697 ($x=0.015$) and Q1715 ($x=0.064$) at $T_L=1.4$ K and low current densities. The inverse Mn temperature is plotted versus the inverse electron temperature for Q1715 in the inset. The solid lines represent the calculated results of either Eq. (5) or (6).

energy transfer to the 2DEG τ_e should be related to their increase in temperature by the heat balance equation

$$c_v \Delta T_e = (I/W)^2 \rho_{xx} \tau_e, \tag{4}$$

where the electronic heat capacity per unit area is given by $c_v=(\pi^2/3)(k_BT/E_F)nk_B$, W is the width of the Hall bar, ρ_{xx} the resistivity, and n the electron density. From the experimental values for low currents, which are given by the slope of the straight line in Fig. 4, $\rho_{xx}=115\ \Omega$, $n=4.2\times10^{12}\ \mathrm{cm}^{-2}$, and $E_F=220$ meV, we find $\tau_e\sim7\times10^{-11}$ s, which is a reasonable value for a 2DEG in a QW.[18]

Deviation from the I^2 dependence at higher currents indicates that lattice heating effects are no longer negligible; however, due to the large heat capacity of the HgTe lattice compared to that of the 2DEG, any increase in the lattice temperature T_L is assumed to be negligible, particularly for $I\leqslant100$ μA.

At a given current, the temperature of the electrons is much higher than that of the Mn ions. As discussed in Refs. 10 and 19, the hot carriers will lose some of their excess energy to the Mn ion system via spin-flip scattering as well as to the lattice. The heat loss from the Mn system to the lattice is determined by the spin lattice relaxation rate (SLR). In very dilute systems with $x<0.01$, where Mn ions are isolated entities, the spin-lattice relaxation time is extremely long. However, it decreases by several orders of magnitude with an increasing concentration of Mn ions, when clusters of three or more magnetic ions are formed.[20] Under the influence of steady-state heating, the resulting spin temperature T_{Mn} will exceed the lattice temperature. The temperature difference is determined by the energy flux and the SLR.

If the temperature difference between Mn and the lattice is small then according to the rate equation model of König *et al.*[19]

$$\frac{1}{T_{Mn}}-\frac{1}{T_L}=\frac{\tau_{SL}}{\tau_{SL}+(\tau_{e\text{-}Mn}+\tau_s)}\left(\frac{1}{T_e}-\frac{1}{T_L}\right), \tag{5}$$

where τ_{SL}, $\tau_{e\text{-}Mn}$, and τ_s are the spin-lattice, electron-Mn ion, and electron spin relaxation times, respectively. By means of recursive substitution, this equation can be exactly rewritten as

$$\frac{T_{Mn}-T_L}{T_L}=\frac{ay}{1+y(1-a)}, \tag{6}$$

where

$$a=\frac{\tau_{SL}}{\tau_{SL}+(\tau_{e\text{-}Mn}+\tau_s)} \tag{7}$$

and

$$y=\frac{T_e-T_L}{T_L} \tag{8}$$

The condition that $T_{Mn}-T_L$ is small, is fulfilled at low current densities where in addition $T_e-T_L=bI^2$, e.g., see Fig. 4. The subsequent application of either Eq. (5) or (6) for these current densities results in values which are in very good agreement with experiment as can be seen in Fig. 5. Good agreement is obvious in the inset when $T_{Mn}-T_L$ is small, whereas a large deviation can be seen at higher Mn temperatures. Furthermore, the ratio of $\tau_{SL}/(\tau_{e\text{-}Mn}+\tau_s)$ has been determined from the resulting value of a and is listed in Table II for both QW's. If τ_{SL} and its Mn dependence is assumed to be similar to that of other Mn containing II-VI hererostructures,[10] then the Mn dependence of τ, where $\tau=\tau_{e\text{-}Mn}+\tau_s$, can be determined according to

TABLE II. Experimental values for a, b, and $\tau_{SL}/(\tau_{e\text{-}Mn}+\tau_s)$, i.e., $a/(1-a)$.

	x	$b(\mathrm{K}/\mu\mathrm{A}^2)$	a	$\tau_{SL}/(\tau_{e\text{-}Mn}+\tau_s)$
Q1697	0.015	5.2×10^{-4}	0.94 ± 0.02	16.7 ± 6.0
Q1715	0.064	2.0×10^{-4}	0.50 ± 0.10	1.0 ± 0.4

$$\frac{\tau_{SL}(0.015)}{\tau_{SL}(0.064)}\frac{\tau(0.064)}{\tau(0.015)} = R_{SL}R^{-1} = R_{exp}, \quad (9)$$

where R_{SL}, R^{-1}, and R_{exp} are the corresponding ratios. Using $R_{exp} \approx 17$ and values for other II-VI materials,[10] i.e., $R_{SL} \approx 70 \pm 30$, results in $R \approx 4$. In other words, $(\tau_{e\text{-}Mn} + \tau_s)$ also increases with decreasing Mn concentration.

IV. CONCLUSIONS

By analyzing nodes in the beating pattern of SdH oscillations in a M2DEG in $Hg_{1-x}Mn_xTe(001)$ QW's, the temperature of the electrons as well as that of the Mn ions have been determined. When $T_{Mn} - T_L$ is small, experimental values of T_{Mn} are in excellent agreement with the predictions of a rate equation model. This leads to estimated values for the ratio of $\tau_{SL}/(\tau_{e-Mn} + \tau_s)$. These ratios are consistent with the shorter spin-lattice relaxation times for other II-VI materials at higher Mn concentrations,[10] as well as lower values of $(\tau_{e\text{-}Mn} + \tau_s)$.

ACKNOWLEDGMENTS

The authors thank D. R. Yakovlev for numerous discussions. The financial support of the Deutsche Forschungsgemeinschaft for SFB410, the DARPA SpinS program, the National Natural Science Foundation of China, Grant No. 10374094 (Y.S.G.), and the Chinese special funds for major state basic research, Project No. G001CB3095 (Y.S.G.) is gratefully acknowledged.

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