Current heating of a magnetic 2DEG in Hg$_{1-x}$Mn$_x$Te/Hg$_{0.3}$Cd$_{0.7}$Te quantum wells

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Heating caused by electrons with excess kinetic energy has been investigated in a magnetic two-dimensional electron gas, M2DEG, in Hg$_{1-x}$Mn$_x$Te/Hg$_{0.3}$Cd$_{0.7}$Te (001) quantum wells. The temperature of the Mn ions, $T_{\text{Mn}}$, has been determined by the node positions in the beating pattern in Shubnikov-de Haas oscillations. The experimental dependence of $T_{\text{Mn}}$ on current and therefore on electron temperature, is in excellent agreement with a rate equation model. Results with this model show that the energy transfer rate from the electrons to the Mn system is proportional to the Mn concentration.

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Interesting new physics has resulted from the study of a two dimensional electron gas, 2DEG, which is subjected to additional interactions. For example the Rashba spin-orbit, s-o, interaction has been the subject of numerous investigations of III-V heterostructures. The Rashba s-o coupling is particularly strong in narrow gap HgTe quantum wells, QWs, with an inverted band structure. The recently introduced magnetic 2DEG in which magnetic ions (usually Mn ions) are exchange coupled to the 2DEG is another example. Spin interactions and spin dependent transport and localization have been investigated in these systems. In addition, Rashba, Zeeman and Landau effects have been shown to be of comparable magnitude in a M2DEG found in Hg$_{1-x}$Mn$_x$Te quantum wells. The giant Zeeman splitting caused by the $sp-d$ exchange interaction can be efficiently suppressed by increasing the manganese temperature, while the spin-orbit splitting only depends on the asymmetry of the QW and is not sensitive to temperature.

Recently, Keller et al. have found an efficient energy transfer from the photo-excited carriers to the Mn system, which raised the temperature of the magnetic ion system in a Zn$_{1-x}$Mn$_x$Se/Zn$_{1-x}$Be$_x$Se M2DEG. However, the power of the laser radiation is much higher than that of the current normally employed in a magneto-transport 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$_x$Te/Hg$_{0.3}$Cd$_{0.7}$Te (001) QWs. Samples with different Mn concentrations have been studied as a function of current by means of their Shubnikov-de Haas, SdH, oscillations. 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.

A series of n type Hg$_{1-x}$Mn$_x$Te/Hg$_{0.3}$Cd$_{0.7}$Te (001) QWs were grown by molecular beam epitaxy, MBE, on Cd$_{0.99}$Zn$_{0.01}$Te (001) substrates. The QWs were modulation doped using Cd$_{12}$ as a doping material. The Hg$_{1-x}$Mn$_x$Te 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. Standard Hall bars with a width, W, of 200 μm were fabricated by wet chemical etching. A 200 nm thick Al$_2$O$_3$ film was deposited on top of the structure, which serves as an insulating layer. Ohmic indium contacts were fabricated by thermal bonding. Magneto-transport 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 $3.3 \times 10^{12}$ cm$^{-2}$ and $5.2 \times 10^{4}$ cm$^2$/Vs for Q1697 ($x = 0.015$), and $4.2 \times 10^{12}$ cm$^{-2}$ and $2.0 \times 10^{4}$ cm$^2$/Vs for Q1715 ($x = 0.064$) at 4.2 K for zero gate voltage from low magnetic field Hall measurements.

Fig. 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$_x$Te/Hg$_{0.3}$Cd$_{0.7}$Te samples, the total spin splitting energy is a combination of Rashba s-o and giant Zeeman splitting energies. The Rashba s-o effect is due to the structure inversion asymmetry, SIA, of the quantum well which is small for the present samples. However the Rashba effect does not depend on temperature 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., $\leq 400$ μA and $\leq 1.2$ mA for Q1697 and Q1715, respectively.

Only giant Zeeman splitting depends on the temperature of the Mn ions, $T_{\text{Mn}}$, according to the phenomenological expression:

$$E_Z = g_0 \mu_B B - \frac{\Delta E_{\text{max}} B_{5/2}(5g_M \mu_B B)}{2k_B(T_{\text{Mn}} + T_0)}$$

(1)

where $g_M = 2$, $B_{5/2}(x)$ is the Brillouin function for a spin of $S=5/2$, empirically modified by using a rescaled temperature, $T_{\text{Mn}} + T_0$, to account for antiferromagnetic spin-magnetic spin interaction, and $(\Delta E)_{\text{max}}$ is the saturated split-
The energy relaxation time associated with energy transfer to the 2DEG, $\tau_e$, is the width of the Hall resistance oscillations and can be used to determine the $T_{\text{Mn}}$. To accomplish this, the nodes in SdH oscillations at known lattice temperatures and a current of 1, 10, 20, 50, 75, 100, 150, 200, 300 and 400 $\mu$A, respectively. The plots are offset 2 $\Omega$ 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 $\Omega$ for clarity.

where the electronic heat capacity per unit area is given by $c_v = (\pi^2/3)(k_B T/E_F) n k_B$, $W$ is the width of the Hall bar, and $n$ the electron density. From the experimental values for low currents, which is indicated by the straight line in Fig. 4, $n = 4.2 \times 10^{12}$ cm$^{-2}$ and $E_F = 220$ meV, we find $\tau_e \approx 8 \times 10^{-11}$ s, which is a reasonable value for a 2DEG in a QW.

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 $I \leq 100$ $\mu$A.

If the temperature difference between Mn and the lattice is small then according to the rate equation model
By means of recursive substitution, this equation can be exactly rewritten as

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

(4)

where

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

(5)

and

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

(6)

The $T_{\text{Mn}} \approx T_L$ condition is fulfilled at low current densities where in addition $T_e - T_L = bI^2$, e.g., see Fig. 4. The subsequent application of Eq. (4) for these current densities results in values which are in very good agreement with experiment as can be seen in Fig. 4. Furthermore, the ratio of $\frac{\tau_{\text{SL}}}{(\tau_{e-\text{Mn}} + \tau_s)}$ has been determined from the resulting value of $a$ and is listed in Table II for both QWs. If $\tau_{\text{SL}}$ and its Mn dependence is assumed to be similar to that of other Mn containing II-VI heterostructures, then the Mn dependence of the total characteristic time of energy transfer from the 2DEG to the Mn, $\tau$, can be determined according to

$$\frac{\tau_{\text{SL}}^{0.015}}{\tau_{\text{SL}}^{0.064}} = R_{\text{SL}} \cdot R^{-1} = R_{\text{exp}}.$$  

(7)

where $\tau = \tau_{e-\text{Mn}} + \tau_s$, and $R_{\text{SL}}, R^{-1}$ and $R_{\text{exp}}$ are the corresponding ratios. Using $R_{\text{exp}} \approx 12$ and values for other II-VI materials, i.e., $R_{\text{SL}} \approx 40$ to 100, results in $R \approx 6$. In other words, the total relaxation time of the 2DEG is given by $\tau = (\tau_{e-\text{Mn}} + \tau_s) \propto 1/x$.

At a given current, the temperature of the electrons is much higher than that of the Mn ions. As discussed in Refs. 10 and 16, 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 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. Under the influence of steady-state heating, the resulting spin temperature, $T_{\text{Mn}}$, will exceed the lattice temperature. The temperature difference is determined by the energy flux and the SLR time.

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

| $x$ | $b (\mu\text{A}^{-2})$ | $a$ | $\tau_{\text{SL}}/(\tau_{e-\text{Mn}} + \tau_s)$ |
|-----|------------------------|-----|---------------------------------|
| Q1697 | 0.015 5.2 $\times$ 10$^4$ | 0.94 $\pm$ 0.02 | 16.7 $\pm$ 6.0 |
| Q1715 | 0.064 1.9 $\times$ 10$^4$ | 0.58 $\pm$ 0.10 | 1.4 $\pm$ 0.5 |
By analyzing nodes in the beating pattern of SdH oscillations in a M2DEG in Hg$_{1-x}$Mn$_x$Te(001) QWs, the temperature of the electrons as well as that of the Mn ions have been determined. When $T_{\text{Mn}} - T_1$ is small, experimental values of $T_{\text{Mn}}$ are in excellent agreement with the predictions of a rate equation model. This leads to values for the ratio of $\tau_{SL}/(\tau_{e-Mn} + \tau_s)$. These ratios are consistent with the expected shorter spin-lattice relaxation times at higher Mn concentrations. An analysis based on this model results in the Mn dependence of the total time for energy transfer from the 2DEG to the Mn ion system, which is inversely proportional to the Mn concentration.

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