Relaxation of magnetization in Cd$_{1-x}$Mn$_x$Te diluted magnetic semiconductors under illumination

M. Smith, A. Dissanayake, and H. X. Jiang
Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601
L. X. Li
Cleveland Crystal, Inc., Cleveland, Ohio 44110

Relaxation of thermoremanent magnetization (TRM) of Cd$_{1-x}$Mn$_x$Te diluted magnetic semiconductors (DMS) in the spin-glass state have been studied under light illumination. The relaxation of TRM can be described well by a power law decay, \( M(t) = M(t_0) t^{-\alpha} \) \((t > t_0, t_0 \sim 2\ s)\). The variations of the decay parameter \( \alpha \) with the illumination light intensity has been measured and a relation which indicates that \( \alpha \) is proportional to the photogenerated carrier concentration \( n \) has been observed.

The diluted magnetic semiconductors (DMS) are a group of materials which have attracted a great deal of attention for many years because of their unique properties for understanding many fundamental physics as well as their promising practical applications. \(^1\) \(^2\) The magnetic behavior of different kinds of DMS show many common characteristics, which can be understood on the basis of a random array of localized magnetic moments coupled by isotropic antiferromagnetic interaction. \(^3\) Many aspects of this interaction between magnetic ions are still under investigation. One of the interesting and important subjects in the DMS is the spin-glass (SG) state at low temperatures. It is well established in DMS that there exists a paramagnetic to a SG transition at low temperatures because of randomness of magnetic ion distribution and spin-spin interactions. The transition temperature or freezing temperature \( T_f \) depends on magnetic ion composition, \(^4\) \(^5\) magnetic field, \(^6\) and history of the system. Although some work has been devoted to study SG dynamics in the DMS previously, \(^7\) \(^-\) \(^10\) the understandings of the dynamic process of SG formation and transformation as well as the relaxation in the SG state are still far from complete.

In this paper, we report the studies of the relaxation of thermoremanent magnetization (TRM) of Cd$_{1-x}$Mn$_x$Te in the SG state under light illumination. A power law time dependence of TRM relaxation has been observed and the decay parameter at different excitation light intensities has been measured. The main results reported in this paper are the investigations of the spin-spin interaction of the magnetic ions in the SG state as affected by photogenerated electrons and holes. We have measured TRM under light illumination at different conditions and the results have been compared to those obtained in the dark.

The sample used for this study was a Cd$_{0.74}$Mn$_{0.26}$Te single crystal provided by Cleveland Crystal, Inc. It was grown by temperature gradient technique and nominally undoped. However, photoluminescence measurements of a bound exciton transition indicated a low concentration of impurities in the samples. The size of the sample was a few cubic millimeters. The magnetization was measured by a superconducting quantum interference device (SQUID) magnetometer (Quantum Design MPMS5). In order to study the effects of photoexcitation to the relaxation of TRM, a quartz fiber optic probe was used with the SQUID. The fiber optic probe was made of an optic fiber bundle with a diameter of about 2 mm. One end of the fiber optic probe was in the sample chamber within a few mm from the sample and the other end was outside the SQUID. A mercury lamp with a set of neutral density filters was used as an excitation source.

We have measured the susceptibility of a Cd$_{0.74}$Mn$_{0.26}$Te sample under the field-cooled (FC) and zero-field-cooled (ZFC) conditions to determine the freezing temperatures \( T_f \) of the SG state. The data show that \( T_f \) is about 4.2 \( \pm \) 0.2 K, which is consistent with previous measurements. \(^5\) \(^-\) \(^7\) In this paper, we only report relaxation of TRM in the SG state, or at temperatures below \( T_f \). We did not observe any remanent magnetization above \( T_f \).

Figure 1 is the plot of relaxation of magnetization at \( T=1.7\) K and measured at \( B=100\) Oe. The experiment was performed by cooling down the system with the magnetic field on \((B=1\) T\), i.e., under FC condition, then by reducing the field to \( B=100\) Oe after the temperature has reached 1.7...
The decay parameter $\gamma$ is directly correlated with the decay cases. At all temperatures, the magnetization relaxes faster decreases linearly with increasing of temperature for both of temperature in the dark (000) and under illumination (*#a). We have to point out that the initial condition for the relaxation depends on the waiting period before the measurement. In order to minimize the difference in the initial condition, we begin to collect the relaxation data under illumination and in the dark at the same time so that direct comparison between two cases can be made here. Previously, a power law decay of magnetization in DMS has been observed. Here, we also find that the experimental results shown in Fig. 2 can be described quite well by a power law decay,

$$M(t) = M_0e^{-\alpha t} (t > t_0, t_0 \approx 2 \text{ s}),$$

both in the dark and under illumination, where $\alpha$ is the decay parameter. The fitted values in Fig. 2 are $\alpha = 2.6 \times 10^{-2}$ and $5.4 \times 10^{-2}$ and $M_0 = 9.9 \times 10^{-6}$ and $9.4 \times 10^{-6}$ emu/g for the conditions in the dark and under illumination, respectively. The decay parameter $\alpha$ is directly correlated with the decay rate. Therefore, the experimental results indicates that the decay rate is about a factor of 2 larger under illumination than that in the dark.

Figure 3 are the plots of decay parameter $\alpha$ as a function of temperature in the dark (000) and under illumination (***). We see that $\alpha$ increases as light intensity increases. Relaxation of magnetization under illumination compared to that in the dark. The difference between $\alpha$ under illumination and in the dark becomes smaller as temperature approaches to $T_f$. Eventually, $\alpha$ approaches to zero at the freezing temperature $T_f$. Dependence of $\alpha$ on temperature $T$ can be described by a linear relation, $\alpha = a - bT$ ($T < T_f$). Extrapolating from $\alpha = 0$, we obtain $T_f$ to be $4.2 \pm 0.2$ and $4.5 \pm 0.2$ K in the dark and under illumination, respectively. We have also measured the magnetization of ZFC vs temperature under illumination and in the dark, we cannot determine whether or not $T_f$ has been changed under illumination because the difference between the values of $T_f$ in the dark and under illumination is within the experimental uncertainty. However, the values of $T_f$ extrapolated from $\alpha = 0$ in Fig. 3 are consistent with the freezing temperature $T_f (=4.2 \pm 0.2$ K) obtained from the FC susceptibility measurement within the experimental uncertainty. The results in Fig. 3 tells us that we can also determine the freezing temperature $T_f$ of the SG state by measuring the temperature dependence of the relaxation parameters of magnetization.

We have also measured the decay parameter $\alpha$ of TRM at a fixed temperature ($T = 2$ K) under photoexcitation with different light intensities. Figure 4 shows a plot of $\alpha$ vs the square root of excitation light intensity, $I^{1/2}$. The magnetic field for the measurements was 100 Oe and the field applied during the cooling down was 1 T. As we expected, the exponent $\alpha$ increases as light intensity increases. Relaxation of magnetization obtained under illumination with different light intensities can be described quite well by the power law decay. We see that $\alpha$ increases linearly with the square root of light intensity, $\alpha \approx I^{1/2}$. The insert of Fig. 4 shows $\alpha$ vs light intensity $I$. One obvious mechanism which may be responsible for...

![FIG. 2. Decay of magnetic susceptibility of TRM of a Cd$_{0.74}$Mn$_{0.26}$Te sample in the dark (000) and under illumination (***). The solid lines are the least-squares fit using a power law decay of Eq. (1).](image)

![FIG. 3. The decay parameter $\alpha$ as a function of temperature in the dark (000) and under illumination (***). The solid lines are the least-squares fit using $\alpha = a - bT$, where $a$ is $3.8 \times 10^{-2}$ and $8.7 \times 10^{-3}$ and $b$ is $9.0 \times 10^{-3}$ and $1.9 \times 10^{-2}$/K in the dark and under illumination, respectively.](image)

![FIG. 4. A plot of $\alpha$ vs the square root of excitation light intensity, $I^{1/2}$. The magnetic field for the measurements was 100 Oe and the field applied during the cooling down was 1 T. As we expected, the exponent $\alpha$ increases as light intensity increases. Relaxation of magnetization obtained under illumination with different light intensities can be described quite well by the power law decay.](image)
constant in units of cm$^4$. Here $G$ is the carrier generation rate writing as $G = \alpha_n \Phi / h \omega$, with $h \omega$ being the excitation photon energy, $I$ the light intensity in units of W/cm$^2$, $\alpha_n$ the absorption coefficient, and $\eta$ the quantum efficiency—number of electrons generated per each absorbed photon. Under continuous and constant intensity light illumination, the photogenerated electrons and holes will be under equilibrium and so we have $dn/dt = 0$. We should also have the condition $n = p$ since our samples are undoped. Then we have

$$n = (G \eta/C)^{1/2} = AI^{1/2},$$

where $B_0$ is the decay parameter $\alpha$ in the dark ($I = 0$), and $B_1$ (in units of cm/W$^{1/2}$) is a proportionality constant. In Fig. 4, we have plotted the least-squares fit of data to Eq. (4) as a solid line.

In conclusion, effects of carriers, which are generated by photoexcitation, to the relaxation of TRM of SG in Cd$_{0.74}$Mn$_{0.26}$Te DMS have been studied. A power law decay both in the dark and under illumination has been observed. The decay parameter $\alpha$ as a function of light intensity has been measured at different temperatures. We found that the decay parameter under illumination increases linearly with the photogenerated carrier concentration. More detailed experimental results and discussions, including the results for different Mn concentrations, will be reported elsewhere.

We acknowledge many helpful discussions with J. Y. Lin, G. Wysin, M. O’Shea, and C. Sorensen. This work is supported by the National Science Foundation under Grant No. DMR 91-18818 and OSR 92-55223.

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