Persistent photoconductivity in II-VI magnetic two-dimensional electron gases

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Persistent photoconductivity is studied in ZnSe/(Zn,Cd,Mn)Se two-dimensional electron-gas structures as a function of Mn concentration. Measurements of spectral photoconductivity, photoinduced transient spectroscopy, and deep-level transient Fourier spectroscopy show the presence of a deep trap located 2.1 eV below the conduction band at near room temperature. The buildup of persistent photoconductivity and its decay kinetics are formulated in accordance with the large lattice relaxation model. Implications of the presence of Mn in the two-dimensional electron gas are discussed. [S0163-1829(99)04908-5]

Magnetic two-dimensional electron gases (2DEGs) form a class of heterostructures in which two-dimensional (2D) electrons within a modulation-doped semiconductor quantum well are exchange coupled with local moments.[1] The most thoroughly studied systems of this type are comprised of modulation-doped (Zn,Cd,Mn)Se quantum wells located between *n*-doped ZnSe barriers and are found to exhibit striking magnetoelectronic properties, such as a completely spin-resolved (and often spin-polarized) quantum Hall effect even at large filling factors[2] and a giant positive magnetoresistance at low magnetic fields.[3] During earlier transport studies, it was noticed that these magnetic 2DEGs exhibit a strong persistent photoconductivity (PPC) that becomes more pronounced when the Mn^{2+} concentration is increased. The enhanced PPC in magnetic 2DEGs is also accompanied by a decrease in sample mobility, suggesting a connection between the deep traps introduced by the magnetic ions and enhanced Coulomb scattering. An understanding of the origin of the PPC may, hence, be important if sample mobility is to be improved. Further, the observation of PPC at relatively high temperatures may be of relevance to device schemes that exploit the presence of PPC for transient gratings and holography.[4] The aim of this Brief Report is to examine the characteristics of the PPC in magnetic 2DEGs and seek empirical correlations with the magnetic composition.

The heterostructures in this study are grown on (100) GaAs substrates following the growth of a 2-μm-thick ZnSe buffer using molecular-beam epitaxy. Samples consist of a modulation-doped single quantum well (10.5 nm) in which the symmetrically placed *n*-type ZnSe doping layers (25 nm) are spaced 12.5 nm from the well region by intrinsic ZnSe barriers. The well is a digital alloy of $(Zn_{0.82}Cd_{0.18}Se)_{m-f}(MnSe)_f$ with $m=5$ and the 2D spin concentration $f=0$, 0.125, 0.25, and 0.5 (samples *A*, *B*, *C*, and *D*, respectively). Details of sample fabrication and routine characterization are given elsewhere.[2,3] Previous experimental measurements have confirmed the formation of 2DEG at the ZnSe/Zn(Cd,Mn)Se interface.[2]

Upon illumination with a photon energy of 2.1 eV or higher, PPC is observed in both the magnetic and nonmagnetic 2DEGs as electrons are excited from a deep trap into the lowest confined subband of the 2DEG. In the nonmagnetic sample, PPC survives only up to 220 K. On the other hand, in the magnetic 2DEGs, PPC is observed up to temperatures between 260 and 282 K, with the maximum temperature for observable PPC increasing with Mn content. This suggests that the trap responsible for PPC in the magnetic 2DEGs is situated in the (Zn,Cd)Se quantum well itself and the presence of Mn enhances the activation energy (electron-capture barrier) required for the return of photoexcited electrons from the conducting channel back into the deep level (see Table I). The PPC buildup is modeled as[5]

$$C_{\mathrm{PC}}(t)=C_d+(C_{\max}-C_d)[1-\exp(-t/\tau_0)], \qquad (1)$$

where C_d is the initial dark conductivity, $C_{\max}$ is the saturation level after illumination, and τ_0 is the buildup time constant. The decay kinetics of PPC can be formulated as

$$C_{\mathrm{PPC}}(t)=C_{\mathrm{PPC}}(\infty)+[C_0-C_{\mathrm{PPC}}(\infty)]\exp[-(t/\tau)^{\beta}], \quad (2)$$

where C_0 is the conductivity buildup level when the illumination is terminated, $C_{\mathrm{PPC}}(\infty)$ is the residual photoconductance at large times, τ is the PPC decay time constant, and β is the PPC decay exponent. Figure 1 shows the buildup and decay transients of PPC in a magnetic 2DEG (for sample *B*) measured at two temperatures, (i) $T=4$ K and (ii) $T=250$ K. The solid curves are the least-squares fits of data with Eq. (1) for PPC buildup and Eq. (2) for the PPC decay.

The variation of the normalized PPC decay as a function of Mn concentration is shown in Fig. 2. For comparison, each curve is normalized such that the conductance is unity at the time at which illumination is switched off. As can be seen, the PPC decays slower with increasing Mn fraction in the 2DEG channel. The degree of retention of PPC also increases with higher Mn content, suggesting that the deep trap interacts with the Mn ions in the sublattice.

TABLE I. Variation of PPC parameters as a function of Mn content.

Sample	2D Mn content f	Capture barrier (meV)	Max PPC temperature (K)	β
A	0	8.5	220	0.763
B	0.125	12.1	260	0.721
C	0.25	20.9	271	0.503
D	0.5	45.5	282	0.481

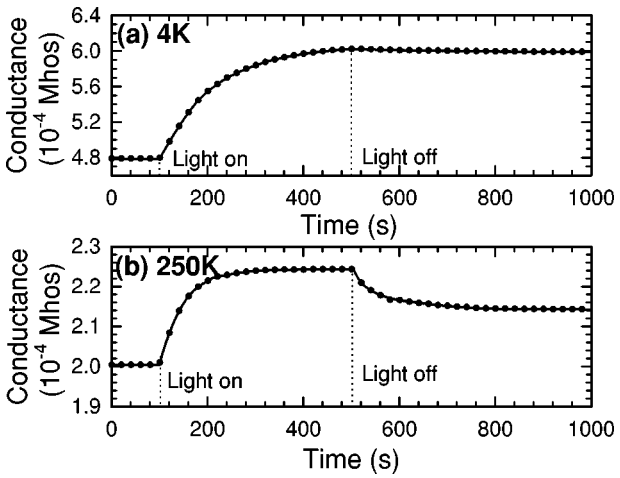

FIG. 1. Buildup and decay of kinetics of PPC associated with ZnSe/Zn(Cd,Mn)Se (for sample *B*) 2DEG measured at (a) 4 K and (b) 250 K. The solid curves are the least-squares fits of experimental data using Eqs. (1) and (2).

The photoexcited electrons remain in the 2DEG well beyond 100 K, exhibiting PPC until there is an activated release of electrons back to the deep trap. This can be seen from Fig. 3, which is a representative Arrhenius plot for sample *B*. Table I lists the various parameters observed as a function of Mn content. The activation energy (capture barrier) is much smaller (by almost an order of magnitude) than observed in III-V heterostructures. This could be argued as a consequence of PPC arising from a trap located very deep in the energy gap very close to $k=0$. The fitted values of the PPC decay exponent β are approximately constant for all temperatures for any given Mn content.

The position of the trap within the band gap is located by measuring the normalized photoconductivity gain spectrum (Fig. 4). The gain spectrum enables a more precise identification of the trap as compared to identifying the maximum of the threshold of the photoconductivity spectrum. The photoconductivity gain peak near 2.1 eV was always observed with a slight variation of the position for both magnetic and nonmagnetic samples. The peaks at 2.65 eV and 2.8 eV are due to electron-hole pairs being generated in the host $Zn_{0.82}Cd_{0.18}Se$ quantum well (QW) and the ZnSe barrier due to band-gap illumination. The measurements were taken after cooling the sample down to 4 K in the dark. A very slow scan was performed with the sample always maintained at 4 K. Correction of the spectra by the lamp response changed the amplitudes but not the threshold positions. The spectrum indicates the position of the trap to be 2.1 eV below the conduction band. We note that there is a well-known zinc vacancy in ZnSe present 0.66 eV (at 4 K) above the valence band, suggesting that the trap in the quantum well region could have a similar origin.

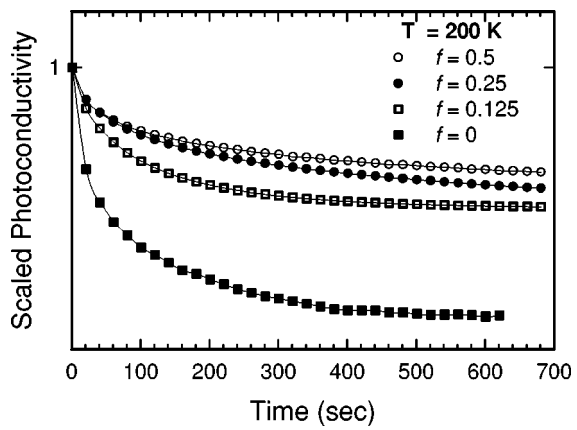

FIG. 2. Decay of PPC for various Mn concentrations in the 2DEG channel at 200 K.

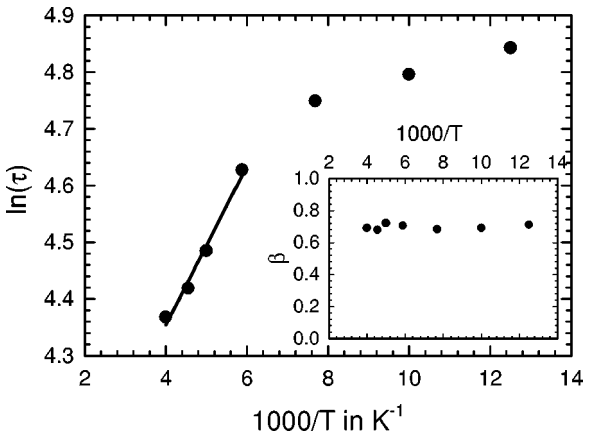

FIG. 3. The Arrhenius plot of PPC decay constant τ (τ vs $1000/T$) for sample *B* gives an activation energy of 17.3 meV for the release of electrons in the 2DEG channel. Inset shows the parameter β as a function of temperature.

The thermal activation energy (E_a) of the trap is measured using photoinduced transient spectroscopy (PITS),

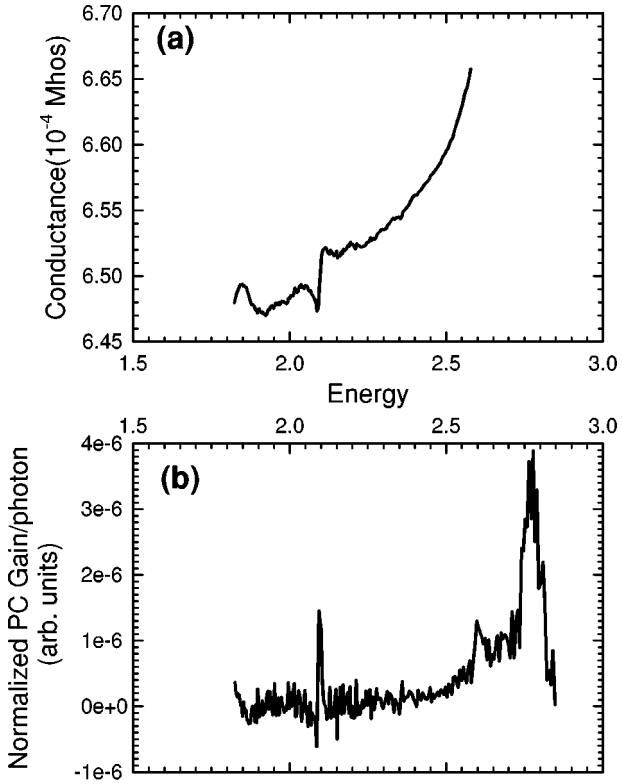

FIG. 4. (a) Shows the photoconductivity spectrum. (b) Normalized photoconductivity gain spectrum of a $f=0.125$ 2DEG (sample *B*). The spike at 2.1 eV indicates the presence of a trap 2.1 eV below the conduction band.

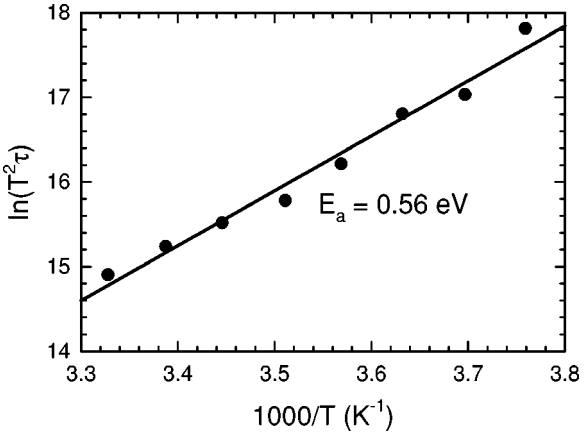

FIG. 5. The Arrhenius plot from the PITS data for sample *B*. The activation energy (E_a) of 0.56 eV can be explained due to the presence of the trap 0.55 eV above the valence band.

wherein the decay of the conductance is observed as a function of temperature.[6] Figure 5 shows the Arrenhius plot obtained from PITS for the magnetic 2DEG. A peak is observed for light excitation of 2.2 eV, which corresponds to thermal activation energy of 0.56 eV at 280 K. We have also observed similar results with deep-level transient Fourier spectroscopy (DLTFS), which yields a thermal activation of 0.576 eV at room temperature. Due to the difficulty in interpreting DLTFS in a complicated heterostructure, we refrain at this point from more detailed discussion of the measurements of the capture cross section and the trap concentration. It has been proposed that the deep Zn vacancy in *n*-type ZnSe regains electrons at adequate enough temperatures by capturing electrons from the *valence* band;[7] this can be viewed as hole emission from the trap. Since the trap responsible for PPC in these magnetic 2DEGs could be related to the Zn vacancy, a similar process may be operational in the present case. Indeed, our PITS and DLTFS measurements are consistent with such an interpretation.

Various theoretical approaches exist for the explanation of PPC. One of the approaches explains PPC on the basis of a spatial separation of the photogenerated electrons and holes by macroscopic potential barriers due to band bending at interfaces.[8] In this model, PPC decay is logarithmic. The Zn vacancies present in the ZnSe barrier that are spatially separated from the electrons inside the 2DEG can lead to some justification of this model in our systems. However, based on the observed decay kinetics, this does not seem to be the predominant process for inducing PPC. Another interpretation attributes PPC to the separation of photoexcited carriers by random local potential fluctuations induced by compositional fluctuations,[9] as in the case of II-VI mixed crystals.[10] We are aware that this model is applicable for bulk systems. However, it is of interest to us because, while we have a digital alloy QW in the direction of the growth, the in-plane composition is random as there is only fractional coverage by MnSe amidst the random placement of the $Zn_xCd_{1-x}Se$ adatoms and the absence of perfect stoichiometry can induce local potential fluctuations in a random alloy. Although the decay kinetics are similar to our observations, the PPC buildup is described by $I(t) \propto (1 - e^{-\alpha t})^2$. Also, in such systems PPC is only observed at high temperatures with a

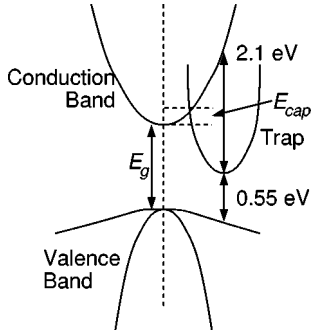

FIG. 6. Energy-level diagram of a magnetic 2DEG. E_{cap} is the electron-capture barrier.

characteristic transition temperature.[7,11] The most widely accepted model for PPC is based on large lattice relaxation accompanying the formation of DX centers.[12] The structural relaxation surrounding the defect makes it a negative-*U* center that is doubly occupied in its ground state. Upon photoexcitation, electrons are released from the defect into the conduction band. As this state is metastable, a barrier to recombination is created by structural relaxation to return, to the DX state. At low temperatures, thermal relaxations are insufficient to cause lattice relaxation; hence the photoexcited electrons remain in the conduction band resulting in PPC. The PPC buildup and decay kinetics are similar to our observations. Furthermore, there is clear experimental evidence for the formation of DX centers as a result of the introduction of both Zn and Mn into *n*-type CdTe.[13–16] This suggests the possibility of similar behavior in (Zn,Cd,Mn)Se alloys with Mn introducing a slightly nonequilibrium configuration. We note that although the photoionization of DX centers in the quantum well region appears to be the dominant mechanism for inducing PPC in our systems, we cannot rule out some contribution to PPC due to spatially separated charges across the 2DEG interface.

A detailed physical model of the deep traps in these heterostructures will have to await microscopic calculations. Here, we develop a plausible picture based on our experimental observations. The data clearly indicates a deep trap in the $Zn_xCd_{1-x}Se$ quantum well which is present 2.1 eV below the conduction band and which is modified by the presence of Mn. At low temperatures when the trap is photoionized, the electrons jump from the trap to the conduction band and remain there due to a repulsive potential barrier preventing them from going back to the DX center. This behavior seems to be enhanced in magnetic samples as can be observed from a comparison of the temperature to which PPC exists between the nonmagnetic and the magnetic samples. The presence of Mn perturbs the lattice and could amplify the existing DX center due to a local nonequilibrium situation in accordance with a large lattice relaxation. However, we reject this possiblity based on the lattice constants of the contributing alloys (lattice mismatch between ZnSe and CdSe= 7%, ZnSe and MnSe=1.8%). As both Cd and Mn occupy the substitutional cation site, the presence of manganese reduces the in-plane strain. Reduction of strain would decrease the activation energy with increasing Mn content, which is in contradiction with our observation. We propose that the introduction of Mn ions into the lattice results in an enhanced electron-electron interaction between the electrons

in the trap and the unpaired $3d^5$ electrons of Mn, leading to a narrowing of the parabolic trap potential, as seen in Fig. 6. On increasing the Mn content the potential narrows even further, leading to a higher repulsive barrier for the electrons to return to the DX center after photoionization. A consequence of this would be an increased activation energy for the electrons inside the 2DEG. Also, during photoionization, for 2DEGs with higher Mn content, the electrons inside the DX center would face an increased effective barrier potential, thus making it harder for them to be transferred to the conduction band. These deep levels appear to be an important contributing factor towards the low mobility in ZnSe-based magnetic 2DEGs. However, at this stage, it is not clear how to estimate the extent of the Coulomb scattering from the presence of the deep traps in the quantum well region and its effect on mobility. Further work on the nature of the interaction between the Mn^{2+} ions and the deep trap will have to be done in order to understand and improve mobility in our structures.

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