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Photo-Carrier Induced Magnetism in III-V Magnetic Alloy Semiconductor Heterostructures

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1. Introduction

Spin-related phenomena in semiconductors have been studying extensively for years. This offers opportunities to develop the new functional devices for "spin electronics". III-V-based magnetic alloy semiconductor (MAS) is one of the materials systems for the study of spin electronics because of its ferromagnetic ordering. It has been found that the strong coupling between carrier spins and local magnetic moments plays important roles in the occurrence of ferromagnetism in III-V MASs. This may mean that the physical properties associated with this phenomenon can be controlled precisely as a function of carrier numbers and/or spin polarity. Up to now, inducement of ferromagnetic order has been found possible by both light illumination [1] and application of an electric field [2] in InMnAs-based heterostructures. A change in the magnetic coercive force by the light illumination has also been demonstrated recently with ferromagnetic *p*-type (In,Mn)As/GaSb heterostructures [3]. In order to understand these important effects quantitatively, we have studied both preparation and photo-carrier induced magnetism for (In,Mn)As/GaSb heterostructures in detail.

2. Experiments

Various types of *p*-(In,Mn)As/GaSb heterostructures were prepared by molecular beam epitaxy on GaAs(100) substrates with Mn content x up to about x = 0.2 [4]. Sometimes, GaSb layers were doped with Te to control intentionally the built-in electric field across the (In,Mn)As/GaSb heterojunction. Substrate temperature T_s for the preparation of an (In,Mn)As layer was T_s = 190-240 °C. Curie temperature T_c of ferromagnetic *p*-(In,Mn)As depends on both growth condition and the amount of incorporated Mn. At the point of writing this abstract, T_c for x = 0.12 samples is 40 – 50 K with nominal hole concentration of $p = 2 - 6\times10^{19}$ cm^{-3}. There is a strong self-compensation effect for the incorporated acceptor Mn. Perpendicular magnetic anisotropy with a well-defined squared hysteresis loop has been observed for some of the samples. This is an indication for the confinement of tensile strain in the (In,Mn)As layer [5], and we call such samples as high quality samples. In any case, ferromagnetic order tends to become loose with decreasing the p value, say below 1×10^{19} cm^{-3}.

As shown schematically in Fig.1, when the heterostructure is irradiated with light, the light path through a very thin (In,Mn)As layer (E_g = 0.4 eV) and is absorbed predominantly in the relatively thick GaSb layer (E_g = 0.8 eV), yielding electrons and holes in the *non-magnetic* GaSb layer. Photo-generated holes are then transferred into the *magnetic* (In,Mn)As layer by the electric field across the interface, and stored there. In the (In,Mn)As layer, an increase in hole numbers enhances the strength of carrier-induced ferromagnetic interaction. Consequently, this results in an increase in magnetization, as well as the photoconductivity, even after the light is turned off. Persistent photoconductivity is noticeable up to around 175 K, whereas the enhanced magnetization eventually vanishes at around 40 K. The induced ferromagnetic interaction is not strong enough to overcome the thermal fluctuation.

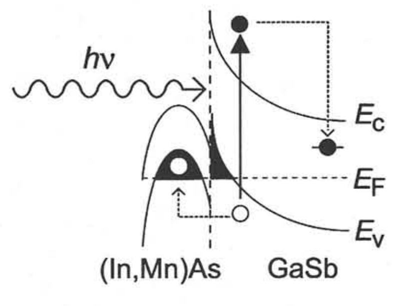

Fig. 1 Schematic band diagram of *p*-(In,Mn)As/GaSb. E_F, E_C, and E_V represent Fermi level, conduction band edge, and valence band edge, respectively.

3. Results and discussion

Wavelength dependencies for both persistent photoconductivity and magnetization enhancement are shown respectively in Fig.2(a) and (b). The experiments have been carried out with the fixed excitation power of about 0.1 mW/cm^2. While persistent photoconductivity is observable throughout the excitation wavelengths of 700 nm - 1.55 μm, the amount of change in magnetization decreases monotonically with increasing the wavelength and vanishes at the wavelength of 1.55 μm ($h\nu = 0.8$ eV). The discrepancy in the wavelength dependence between the two behaviors suggests that holes generated in the GaSb layer are not transferred effectively in the (In,Mn)As layer, especially in case of the 1.55-μm excitation. One likely explanation is to assume another hole accumulation region in the GaSb side of the (In,Mn)As/GaSb interface. This hypothetical region, as shown also in Fig.1 by a black triangular area at the interface on GaSb side, could be anticipated by solving the self-consistent Poisson-Schrödinger equations. Systematically studying the high-field Hall resistance and the magnitude of persistent photoconductivity, we estimate that about 30% of photo-generated holes can be transferred from GaSb to (In,Mn)As layers. More effective charge transfer is desired to realize the photo-enhanced magnetization at higher temperatures. A *p*-(In,Mn)As/n-GaSb:Te heterostructure will provide a stronger electric field across the junction and may be much suitable for the hole transfer process.

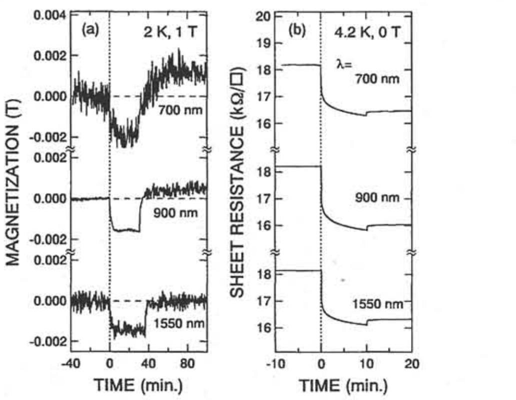

Fig. 2 Changes in (a) magnetization at 2 K under the applied magnetic field of 1 T, and (b) sample resistance at 4 K during the light irradiation with various wavelengths.

Another important aspect of the carrier-induced magnetism is that the strength of the ferromagnetic exchange manifests itself in the magnetic characteristics. One such example is the reduction of coercive force after the light irradiation (Fig.3). The hysteresis loops shown in the figure clearly shows that the process of magnetization reversal begins at a magnetic field lower than that in the dark. The numbers of holes that was accumulated in the (In,Mn)As layers during the light illumination were low 10^{18} cm^{-3}, being about 3% of the background hole concentration, whereas the coercive force is reduced for about 45% at 35 K. The magnitude of reduced coercive force is enhanced with increasing light intensity. This shows a control of magnetization reversal field by a change of carrier concentration.

4. Conclusions

We have grown (In,Mn)As/GaSb samples for the study of photo-carrier induced magnetism and observed the several phenomena attributed to carrier-induced magnetism by light illumination. The importance of strong built-in electric field across the interface for hole transfer has been discussed from the wavelength dependence of photo-induced magnetization. We have observed a decrease in coercive force after the light illumination, and have demonstrated one of the possibilities to control the magnetization reversal process without changing the external magnetic field in III-V MAS.

Acknowledgments

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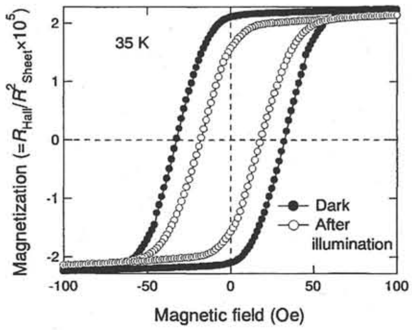

Fig. 3 Magnetization hysteresis curves before (●) and after(O) light Illumination.

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