Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 308-309

E-4-1 (Invited)

Control of ferromagnetic order in selectively *p*-doped GaMnAs-based heterostructures

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While the bandgap and wavefunction engineering are so far limited to *nonmagnetic* semiconductor heterostructures, we aim to broaden its use to *magnetic* heterostructures and to extend the degree of freedom in designing spin-related properties in semiconductors. In this paper, we use the two-dimensional hole gas (2DHG) system in selectively-doped GaAs/*p*-AlGaAs heterostructures together with δ-doping of magnetic (Mn) impurities, and successfully maximize the ferromagnetic order among the Mn spins in GaAs by overlapping the wavefunction of 2DHG with the Mn δ-doping profile.

The mainstream studies of spin-electronic materials based on III-V semiconductors consist of (i) ferromagnet/semiconductor heterostructures such as MnAs/GaAs[1] and (ii) magnetic alloy semiconductors such as InMnAs and GaMnAs.[2-4] Despite extensive studies, in the former system special techniques are required to grow multilayer heterostructures with abrupt interfaces,[5] and much higher Curie temperature T_C is needed for practical application in the latter system (the highest T_C for the past few years was 110K for (GaMn)As).[6] Unlike the random alloy system, here we use δ-doping of Mn in GaAs. Inherent advantages of δ-doping[7] are locally high dopant concentration and high carrier concentration, which can lead to high Curie temperature T_C.[8] Another prospective advantage is easy fabrication of multilayer heterostructures containing Mn δ-doped GaAs layers with excellent interfaces.[9,10]

Mn δ-doped GaAs layers were grown on semi-insulating (SI) GaAs (001) substrates by MBE at the growth temperatures T_s = 200-400°C. Extensive structural analyses revealed that most of the Mn atoms are abruptly confined within a width of 2-3 monolayers (ML) in the zinc-blende structure as substitutional dopants, when the nominal thickness θ_{Mn} of Mn is below 1 ML.[10,11] The Mn doping profiles retained abruptness even at elevated T_s up to 400°C. Although it was possible to incorporate high Mn concentration in the Mn δ-doped GaAs layers, the hole to Mn concentration ratio p/θ_{Mn} was very low and was not enough to realize ferromagnetic ordering.[10,11]

In order to obtain high hole concentration and locally high Mn concentration at the same position, we have grown 0.3 ML Mn δ-doped GaAs/Be-doped *p*-AlGaAs heterostructures by MBE, whose structure is shown in Fig. 1 (a). These *p*-type selectively doped heterostructures (*p*-SDHS) resemble an inverted high electron mobility transistor, where holes are provided from the *p*-AlGaAs layer to the overlying GaAs layer. The thickness d_s of the undoped-GaAs separation layer was a measure to control the interaction between the Mn δ-doped GaAs layer and the 2DHG formed at the GaAs/*p*-AlGaAs interface.

Hall loops at 40 K of 0.3 ML Mn δ-doped GaAs layers grown at 400°C *without* and *with* *p*-SDHS (${d_s}$ = 3 nm) are shown in Fig. 2 (a) and (b), respectively. The hysteresis in the Hall loop of the sample *with* *p*-SDHS clearly indicates ferromagnetic order, while the ferromagnetic hysteresis is absent in the sample *without* *p*-SDHS. The temperature dependence of the sheet resistance ($R_{sheet} - T$) of the samples *without* and *with* *p*-SDHS is plotted in Fig. 2 (c). The sample *without* *p*-SDHS shows insulating behavior due to the low hole concentration. In contrast, the sample *with* *p*-SDHS shows a local maximum of the $R_{sheet} - T$ trace, suggesting that T_C is ~70 K. This value of T_C was confirmed by measuring Hall loops at various temperatures, where hysteresis remained open up to 70 K.

The ferromagnetic order of the samples *with* *p*-SDHS was found strongly dependent on d_s. As shown in Fig. 2 (d), the local maximum temperature of the bump in the $R_{sheet} - T$ trace, which roughly corresponds to T_C, was 45 K at d_s = 0 nm and 70 K at d_s = 3 nm. The Hall loops showed clear ferromagnetic hysteresis at d_s = 0 and 3 nm below T_C. With further increase of d_s to 5 and 10 nm, the bump disappeared. Hysteresis in loops was not observed at d_s = 5 and 10 nm, indicating the absence of ferromagnetic order. The d_s dependence of the ferromagnetic order is explained using the valence band diagram of the heterostructure in Fig. 2 (e). We think that the degree of the overlap of the 2DHG wavefunction and the Mn δ-doping profile directly affects the ferromagnetic ordering and T_C of the heterostructures. T_C was highest (70 K) at d_s = 3 nm, because the overlap was maximum. Further increase of d_s to 5 and 10 nm decreased the overlap of the 2DHG wavefunction and the Mn δ-doped profile, thus weakened the ferromagnetic order.

In order to completely suppress the surface segregation of Mn, and to obtain locally higher Mn concentration in a ideally sharp δ-doped profile, T_s of the Mn δ-doped GaAs layer in the SDHS was lowered from 400°C (at which surface segregation of around 30% Mn dopants was observed in the SIMS depth profile) to 300°C (at which no

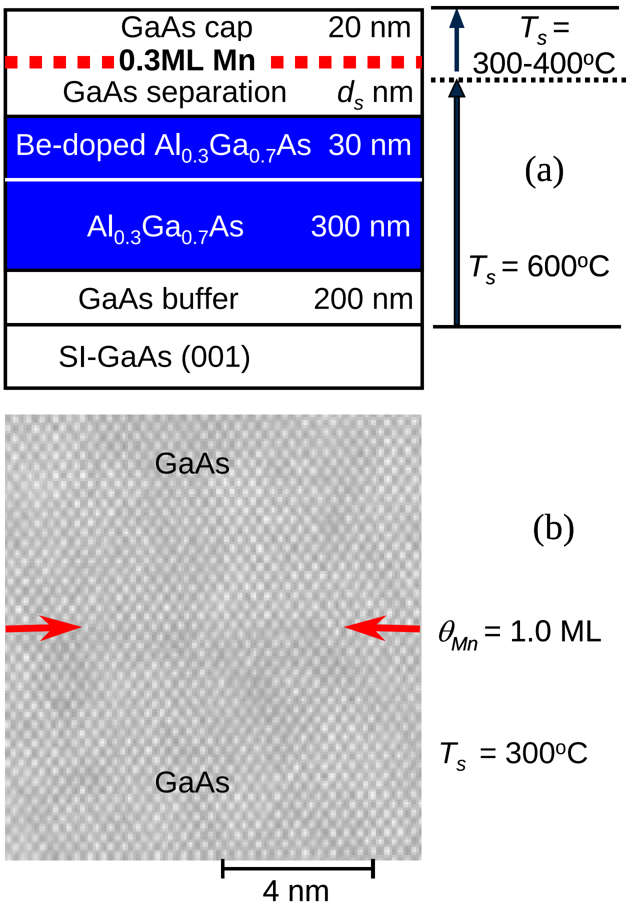

Fig. 1. (a) Sample structure of Mn δ-doped GaAs *with* *p*-type selectively doped heterostructures (*p*-SDHS). The GaAs separation layer thickness d_s was 0 - 10 nm. Holes are supplied from the Be-doped *p*-type $Al_{0.3}Ga_{0.7}As$ layer to the Mn δ-doped GaAs layer in the SDHS. (b) High-resolution TEM lattice image of the Mn δ-doped GaAs layer with θ_{Mn} = 1.0 ML grown at T_s = 300°C.

segregation of Mn was detected).[10,11] The sample examined here was a 0.3 ML Mn δ-doped GaAs (T_s = 300°C)/Be-doped *p*-AlGaAs heterostructure with d_s = 0 nm, as shown in Fig. 1 (a). Low-temperature (LT) annealing was carried out in a nitrogen atmosphere for 15 minutes with various annealing temperatures T_a = 280 - 340°C. It was estimated by the Curie-Weiss fitting that T_C is as high as 172 K for the sample annealed at T_a = 300°C. Note that T_C was dramatically increased from 70 K (grown at T_s = 400°C; as-grown) to 112 K (T_s = 300°C; as-grown), and 172 K (T_s = 300°C; LT-annealed).

In summary, we have shown that the controlled overlap of the wavefunction of the 2DHG and the Mn δ-doping profile in GaAs can lead to ferromagnetic ordering. The highest T_C of the ferromagnetic heterostructures prepared with suitable growth conditions and low-temperature annealing was 172 K. This T_C value is the highest among the reported values in III-V (GaAs, InAs) magnetic semiconductors. Furthermore, we will show that the ferromagnetic order in the *p*-SDSH can be controlled by gate electric field and light irradiation.

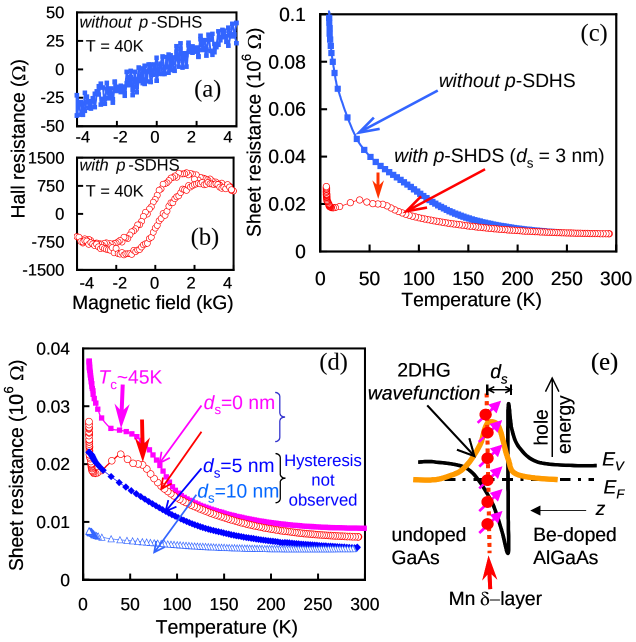

Fig. 2. (a) & (b) Hall loops of 0.3 ML Mn δ-doped GaAs layers grown at 400°C *without* and *with* *p*-SDHS (d_s = 3 nm), measured at 40 K. (c) R_{sheet} $-T$ traces of the samples *without* and *with* *p*-SDHS, respectively. (d) R_{sheet} $-T$ traces of 0.3 ML Mn δ-doped GaAs samples *with* *p*-SDHS for d_s = 0, 3, 5 and 10 nm. (e) Schematic diagram of the valence band profile of the *p*-SDHS, the 2DHG wavefunction, and Mn dopants. E_V and E_F are the valence band top and the Fermi energy, respectively. z is the growth direction.

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