Optical and magnetic properties of InFeP layers prepared by Fe^+ implantation*

Zhou Lin(周 霖)[a)b)], Shang Yan-Xia(尚艳霞)[a)b)], Wang Ze-Song(王泽松)[a)], Zhang Rui(张 瑞)[a)], Zhang Zao-Di(张早娣)[a)], Vasiliy O. Pelenovich[a)], Fu De-Jun(付德君)[a)†], and Kang Tae Won[b)]

[a)] *School of Physics and Technology, Wuhan University, Wuhan* 430072, *China*
[b)] *Quantum-Functional Semiconductor Research Center, Dongguk University, Seoul* 100715, *Korea*

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InFeP layers are prepared by ion implantation of InP with 100-keV Fe^+ ions to a dose of 5×10^{16} cm^{-2} and investigated by optical, magnetic, and ion beam analysis measurements. Photoluminescence measurements show a deep-level peak at 1.035 eV due to Fe in InP and two exciton-related luminescences at 1.426 eV and 1.376 eV in the implanted samples annealed at 400 °C. Conversion electron Mossbauer spectroscopy reveals a doublet corresponding to Fe^{3+} ions in the indium sites. Atomic force microscopy and magnetic force microscopy show that magnetic clusters are formed in the annealing process. The magnetization-field hysteresis loops show ferromagnetic properties persisting up to room temperature with a coercive field of 100 Oe (1 Oe = 79.5775 $A\cdot m^{-1}$), saturation magnetization of 4.35×10^{-5} emu, and remnant magnetization of 4.4×10^{-6} emu.

Keywords: ion implantation, diluted magnetic semiconductor, photoluminescence, Rutherford backscattering/channeling

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1. Introduction

Diluted magnetic semiconductors (DMSs)[1] are a variety of materials with a combination of semiconducting and magnetic properties. In particular, the spins of electrons can be used as an additional degree of freedom that carries the digital bits in multibit memory and other novel spintronic devices. Ideally they are compounds alloying a nonmagnetic semiconductor with a magnetic element, such as GaMnAs. However, in many cases, secondary phases which may be metallic are observed and complicate the structure and properties of the material. Therefore, preparation of DMSs is crucial for practical application of spintronics in the future.[2]

In recent years, much attention has been paid to III–V compound DMSs, which may exhibit ferromagnetism above room temperature.[3–5] The observation of ferromagnetism in Mn-doped GaAs up to 100 K has aroused the interest in searching for semiconductors which exhibit ferromagnetism at even higher temperatures.[6] In III–V narrow-bandgap semiconductors, InP with Fe or Mn dopant exhibits potential for higher critical temperatures as predicted by theoretical calculations. Experimentally, room-temperature (RT) magnetism has been observed in Mn-doped GaAs, Fe-doped GaAs, Co-doped ZnO, and CdMnS.[7–10] However, in the case of InP, few studies of Fe-incorporated DMS were reported.[11] In this paper, we report on results of optical and magnetic properties of InFeP layers prepared by Fe^+ ion implantation.

2. Experiment

The InP wafers were grown by the liquid-encapsulated Czochralski method. They were uniformly implanted with Fe^+ ions at an energy of 100 keV to a dose of 5×10^{16} cm^{-2}. The depth of the dopants in the implanted layer evaluated from the TRIM2003 (transport and recoil of ions in matter) is 100 nm with a straggling of 35 nm. After implantation, the samples were annealed in flowing nitrogen at temperatures ranging from 300 °C–500 °C for 30 min. For photoluminescence (PL) measurement the samples were excited by the 647-nm line of a Kr^+ ion laser with an incident power of 45 mW. The emission from the sample was dispersed with a 0.75-m grating monochromator and detected by a Ge p–i–n diode at 10 K. The composition and structure were measured by Rutherford backscattering and channeling (RBS/C) using a 1.9-MeV H^+ ion beam, with backscattered ions detected at an angle of 155°. Conversion-electron Mossbauer spectroscopy (CEMS) measurement was conducted at room temperature by using a RiKon-5A proportional detector with a mixture of 96% He and 4% CH_4 as a counter gas. A ^{57}Co in Rh matrix source with an activity of 9.25×10^8 *Bq* was used for excitation. The surface morphology of the sample was studied with an SPI3800N atomic force microscope (AFM) and a magnetic force microscope (MFM). The magnetic properties were measured using a superconducting quantum interference device (SQUID) on a Quantum Design MPMS-XL system.

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†Corresponding author. E-mail: djfu@whu.edu.cn

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3. Results and discussion

The photoluminescence (PL) spectra were measured at both room temperature (RT) and 10 K for the implanted samples annealed at 400 °C. The RT PL spectrum shows a broad line, corresponding to band edge transitions. The 10-K PL reveals two peaks located at 1.426 eV and 1.376 eV, as shown in Fig. 1. The high energy line is interpreted as being due to a group of free exciton emission and excitons bound to neutral donors or acceptors.[8] The 1.376-eV line is associated with the transition of electrons from conduction band to acceptor (eA). The acceptor responsible for the eA line can be either C or Zn; both impurities are known to be present in InP grown by the liquid-encapsulated Czochralski technique.[12,13] The deep level emission is a broad band around 1.035 eV, which is attributable to Fe at indium site, phosphorus vacancy, and indium interstitial. From the RBS result, we see that after 400 °C annealing, most defects created by ion implantation are recovered. This fact suggests that the 1.035-eV band is associated with Fe impurity level,[13] with a transition from the conduction band to Fe^{2+}/Fe^{3+} traps in InP matrix, close to the theoretically calculated value.[14,15]

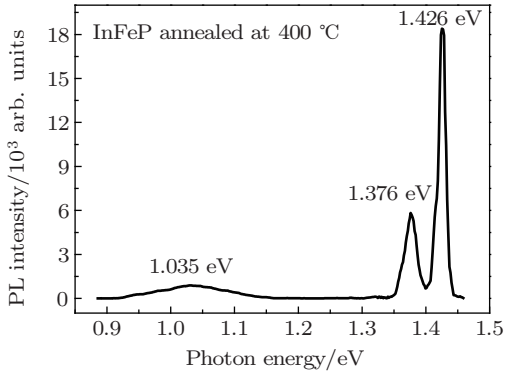


Fig. 1. Low temperature photoluminescence of InFeP annealed at 400 °C.

Figure 2 shows a group of RBS/C spectra of the sample implanted with a dose of 5×10^{16} Fe-atoms/cm^2 followed by annealing at 400 °C and 500 °C. The spectrum for the unimplanted sample is also shown for comparison. The 1.9-MeV H^+ was produced in 2×1.7-MV tandem accelerator and was aligned along the crystalline axis [100] of InP, which was made possible by controlling the movement of the sample mounted on a four-axial goniometer. The result from random RBS spectrum indicates that the concentration of Fe is very low to reveal a weak hump, and the damage induced by ion implantation is negligible. The most interesting is the dechanneling performance of scattered H^+ ions penetrating the sample by skipping the surface damage peak in the aligned spectrum, which clearly illustrates the displacement of target atoms. Some of the Fe atoms were located at the sites of vacancies and became substitution atoms after annealing at high temperatures. We see that the defects were eliminated after annealing at 400 °C, and the performance is better than that annealed at 500 °C. Annealing at higher temperatures does not further improve crystallization, but can produce an abnormal phenomenon which has also been reported in the literature.[16] We deduce that higher annealing temperature favors decomposition of InP, leading to supersaturation of Fe in the InP lattice and to the formation of clusters.

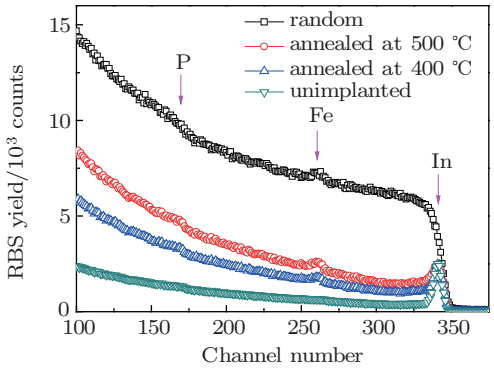


Fig. 2. (color online) RBS/C spectra of an unimplanted sample and two implanted ones annealed, respectively, at 500 °C and 400 °C, in comparison with RBS random spectrum of the sample annealed at 500 °C.

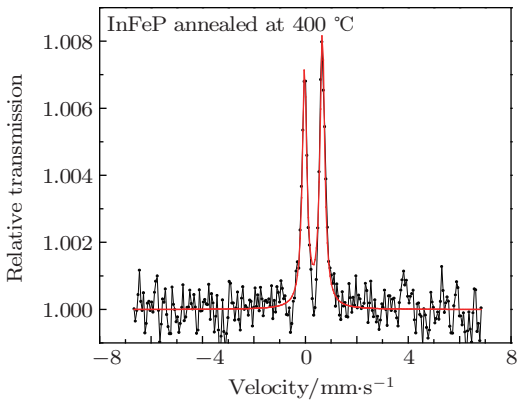


Fig. 3. (color online) CEMS spectrum of the InFeP annealed at 400 °C. The spectral line is fitted by using the Lorentz function.

Figure 3 shows a CEMS spectrum of the InFeP annealed at 400 °C. There is no evidence for the presence of any magnetic sextet, and only a doublet is observed in the spectrum. The Mossbauer parameters of the doublet are as follows: the isomer shift (IS) = (0.31±0.01) mm/s, the quadrupole splitting (QS) = (0.69±0.02) mm/s, and the width of the line $\Gamma = 0.21 \pm 0.03$ mm/s. The observed value of isomer shift indicates that iron atoms are present in the form of Fe^{3+} ions only in the sample. Though the bonding in the cubic III–V compound is predominantly covalent, this is in agreement with the suggestion of substitution of In^{3+} ions by Fe^{3+} ions. A similar result was found in InP implanted with $^{57}Mn^+$, where a singlet spectral line with IS = 0.33 mm/s was observed.[17] The observation of the doublet in this study signifies the presence of a large number of defects surrounding the Fe^{3+} ions,

and these defects can be clearly observed in the RBS/C spectra Fig. 2. However, the nature of these defects remains to be discovered. The width of the line is very narrow and close to the value of the excitation source, which suggests the presence of the defects of only one kind.

The AFM and MFM measurements were carried out for the samples annealed at 300 °C, 400 °C, and 500 °C as shown in Fig. 4. The sample annealed at 300 °C is featureless shown in both AFM and MFM images. However, when the sample is annealed at 400 °C, AFM shows clear white spots and the corresponding MFM image reveals the existence of magnetic clusters as shown by the circle-marked spots in Fig. 4(b). This means that the post-implantation annealing at 400 °C is necessary for observation of the ferromagnetic clusters. Much larger magnetic clusters are observed when the samples are annealed at 500 °C as shown in Fig. 4(c). With annealing temperature increasing, the formation of magnetic clusters is enhanced. The diameter and height of the magnetic clusters are 200 nm–300 nm and 20 nm–30 nm, respectively.

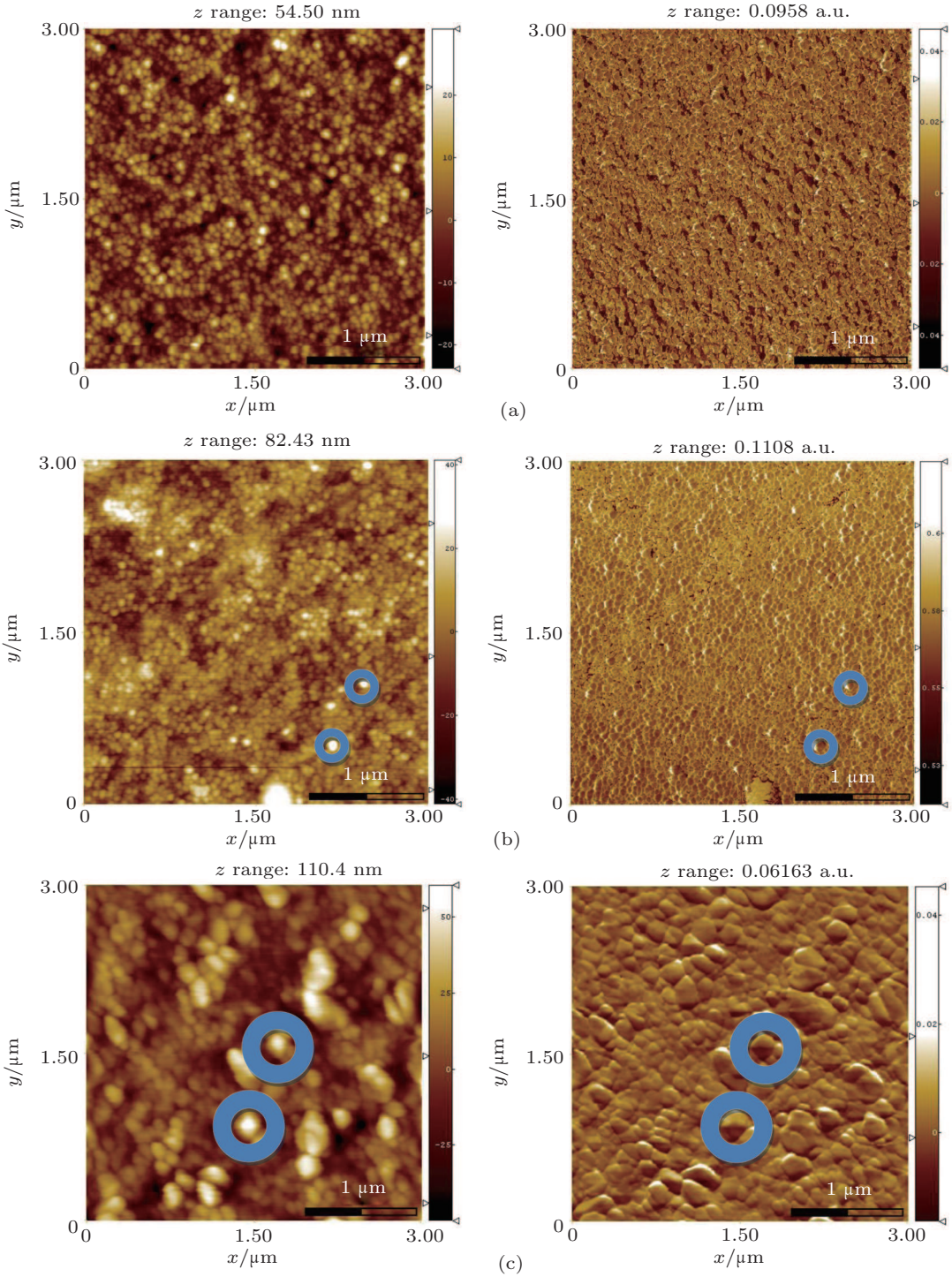


Fig. 4. (color online) AFM (left) and MFM (right) images of InFeP layers prepared by Fe ion implantation followed by annealing at 300 °C (a), 400 °C (b), and 500 °C (c), respectively.

Figure 5 shows the magnetic field dependencies of magnetization of the as-implanted samples and the InFeP samples annealed at 300 °C, 400 °C, and 500 °C, respectively. The well-defined soft hysteresis loop confirms that the InFeP layer is ferromagnetic with a coercive field of 100 Oe (1 Oe = 79.5775 $A \cdot m^{-1}$), a saturation magnetization of 4.35×10^{-5} emu, and a remnant magnetization of 4.4×10^{-6} emu. The weak magnetism of the sample annealed at 500 °C suggests that the sample has a lack of Fe substituting indium sites. Figure 6 shows temperature dependence of magnetization of the InFeP sample annealed at 400 °C for 30 min, revealing a ferromagnetic behavior persisting up to room temperature. It has been found that when the annealing temperature reaches a critical value, the magnetic clusters form but the crystallization is deteriorated, which leads to weakened ferromagnetism.[18]

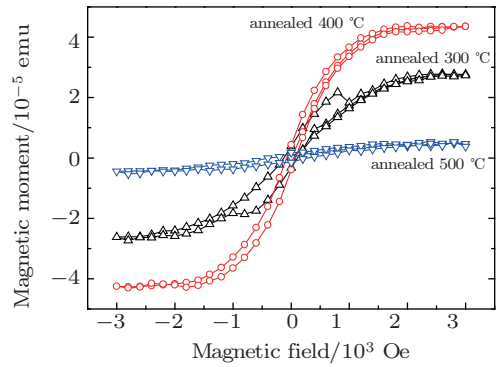


Fig. 5. (color online) Magnetic field dependencies of magnetization of the implanted samples annealed at 300 °C, 400 °C, and 500 °C, respectively.

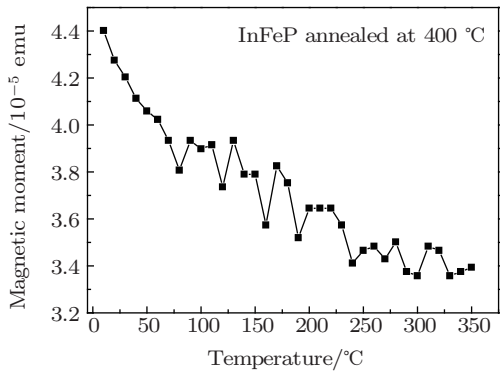


Fig. 6. Temperature dependence of magnetization of the implanted sample annealed at 400 °C.

4. Conclusion

In this paper, we prepared InFeP layers by ion implantation up to 5×10^{16} cm^{-2} followed by annealing at 300 °C–500 °C. Distinct photoluminescences related to the transition from conduction band to Fe^{2+}/Fe^{3+} traps are observed at 1.035 eV. CEMS measurements reveal the presence of a doublet only in the spectrum corresponding to Fe^{3+} ions in the indium sites. AFM and MFM images show that magnetic clusters are formed in samples annealed at 400 °C and 500 °C. Ferromagnetic hysteresis loops are observed in the InFeP layers and the sample annealed at 400 °C shows ferromagnetic properties persisting up to room temperature with a coercive field of 100 Oe, saturation magnetization of 4.35×10^{-5} emu, and remnant magnetization of 4.4×10^{-6} emu.

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