ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Crystal Growth 262 (2004) 287–289

JOURNAL OF CRYSTAL GROWTH

www.elsevier.com/locate/jcrysgro

The magnetic and structure properties of room-temperature ferromagnetic semiconductor (Ga,Mn)N

Fuqiang Zhang[a,b,*], NuoFu Chen[a,b], Xianglin Liu[a], Zhikai Liu[a], Shaoyan Yang[a], Chunlin Chai[a]

[a] *Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China*

[b] *National Microgravity Laboratory of Chinese Academy of Sciences, Institute of Mechanics, Beijing 100080, China*

Received 2 September 2003; accepted 7 October 2003
Communicated by R. Kern

Abstract

Diluted magnetic semiconductor (Ga,Mn)N were prepared by the implantation of Mn ions into GaN/Al_2O_3 substrate. Clear X-ray diffraction peak from (Ga,Mn)N is observed. It indicates that the solid solution (Ga,Mn)N phase was formed with the same lattice structure as GaN and different lattice constant. Magnetic hysteresis-loops of the (Ga,Mn)N were obtained at room temperature (293 K) with the coercivity of about 2496.97 A m^{-1}.
© 2003 Elsevier B.V. All rights reserved.

PACS: 75.50.Pp; 75.70.Ak; 81.05.Ea; 81.05.Zx; 81.15.Hi; 61.82.Fk

Keywords: A1. X-ray diffraction; A3. Ion beam deposition; B1. GaN/Al_2O_3; B2. Ferromagnetic materials

1. Introduction

III–V based diluted magnetic semiconductors (DMSs) [1–5] have demonstrated unique phenomena such as field-effect control of ferromagnetism [6,7], efficient spin injection to produce circularly polarized light [6,8,9], and spin-dependent resonant tunneling [4,6]. But the Curie temperature of DMSs is not high enough. According to a theoretical model considering ferromagnetic behavior of various DMSs [10,11], GaMnN with ~5% Mn and high hole concentrations is predicted to have a Curie temperature above room temperature [11,12]. And GaN-based DMSs are quite promising for various spin-controlled and photonic devices because of the wide gap corresponding to visible light [13]. In order to obtain a heavy doping of Mn in GaN, a highly nonequilibrium growth process is necessary [13]. One of the growth methods is the high-energy Mn-ion implantation whose evident advantage is that the fabrication is easy. But the implanted high-energy Mn ions will seriously destroy the crystal structure which is impossible to restore by post-annealing, and the formation of secondary phase is inevitable [14].

*Corresponding author. Key Laboratory of Semiconductor Materials Science, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, China. Tel.: +86-10-823-04627; fax: +86-10-82304469.

E-mail address: fqzh@red.semi.ac.cn (F. Zhang).

0022-0248/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.jcrysgro.2003.10.031

In this letter, two methods are adopted to overcome the disadvantages of high-energy ions implantation. One is the application of the low-energy ions, which can weaken the damage to crystal structure, and the other is the application of the elevated substrate temperature [12], which helps to restore the crystal structure during the process of implantation and can make the Mn ions reach deeper in the layer of GaN. (Ga,Mn)N samples were prepared by the implantation of low-energy Mn ions into unintentionally doped n-type GaN/Al_2O_3 substrate at different elevated substrate temperatures with mass-analyzed low-energy dual ion beam deposition system. Under optimized substrate temperature and annealing conditions, the solid solution (Ga,Mn)N phase in samples was found with the same lattice structure as GaN and different lattice constants.

The GaN epilayer was prepared by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. (Ga,Mn)N samples were prepared by mass-analyzed low energy dual ion beam deposition system. There are magneto-mass filters in this system with which the manganese can be purified as pure as isotope. Firstly, the manganese ions with energy of 1 keV were uniformly implanted into (0 0 0 1) oriented GaN/Al_2O_3 substrates in the depth of about 60 nm. The dose of manganese ions was about $2.5 \times 10^{14}/cm^2$. During implantation, GaN/Al_2O_3 substrates were heated to 400°C. Secondly, the manganese ions with energy of 100 eV were deposited on the surface of the wafers with the dose of about $1.25 \times 10^{14}/cm^2$ to prevent the implanted manganese ions from diffusing from the surface of the wafer during later annealing and to keep the content of Mn at a high level near the surface. Then, the samples were annealed at 800°C for 30 s under flowing N_2 gas.

X-ray diffraction (XRD) was applied for structure analyses. The wavelength of X-ray radiated from the Cu Kα is 0.1540562 nm. XRD patterns of the samples were measured with $2\theta - \theta$ scan. Other reflections were not found in these X-ray diffraction measurements except the reflections from GaN and Al_2O_3. Fig. 1 is the fine structure of the XRD pattern around (0 0 0 2) reflection from a sample (solid line). The diffraction curve of GaN/Al_2O_3 substrate is the dashed line. There is no change in the diffraction curve of Al_2O_3, because the implanted Mn ions do not affect the structure of Al_2O_3. Compared with the dashed line in Fig. 1, clear diffraction peak from (Ga,Mn)N is observed and the peak difference between (Ga,Mn)N and GaN is 0.357°. It indicates that implanted Mn atoms are incorporated in the wurtzite structure as substitutional atoms of Ga or interstitial atoms in GaN. The solid solution (Ga,Mn)N structure is formed in GaN/Al_2O_3 substrates. The even lattice expand ratio of the (Ga,Mn)N layer is calculated as 1.008% from the peak position of (Ga,Mn)N diffraction patter according to Fig. 1.

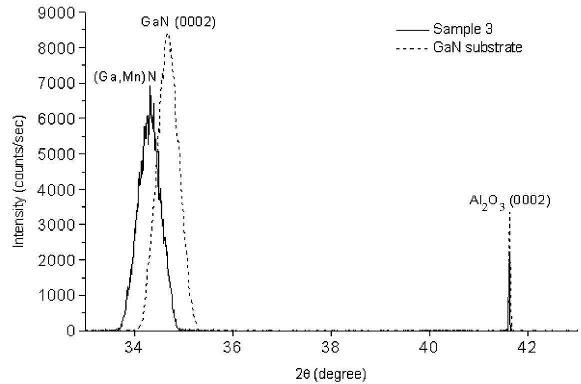

Fig. 1. X-ray diffraction curves of a (Ga,Mn)N sample (solid line) and a GaN/Al_2O_3 substrate (dashed line).

The magnetic properties of the (Ga,Mn)N samples were studied using superconducting quantum interference device (SQUID) magnetometer MPMS7. The measurements were carried out at room temperature (293 K). Fig. 2 shows the typical hysteresis-loop measured by SQUID from a (Ga,Mn)N sample. The highest saturation magnetization and residual magnetization, respectively, are 2.1141×10^{-4} and 2.4002×10^{-5} e.m.u. The largest coercive force in these samples is $2496.97\ A\,m^{-1}$. These results confirm that these (Ga,Mn)N samples are ferromagnetic at room temperature. The magnetization decreases after the magnetic field surpasses the saturation value in Fig. 2. The reason is that the GaN substrate is diamagnetic, and with the increase of magnetic field, the diamagnetic field in GaN becomes obvious.

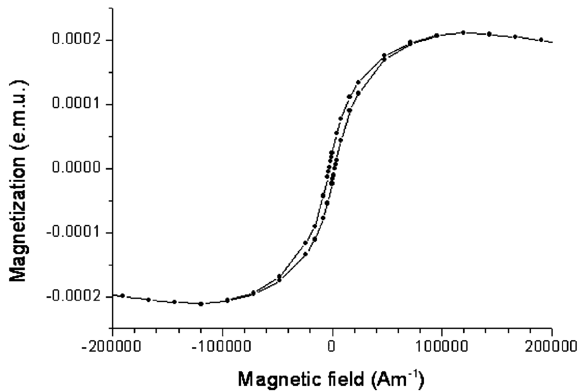

Fig. 2. Magnetic hysteresis-loop measured by SQUID magnetometer from a (Ga,Mn)N sample.

In summary, room-temperature ferromagnetic semiconductor (Ga,Mn)N were prepared with mass-analyzed low energy dual ion beam deposition system. Clear X-ray diffraction peaks from (Ga,Mn)N samples are observed. It indicates that the solid solution (Ga,Mn)N structure is formed with the same lattice structure of GaN and the bigger lattice constant. No evident secondary phase is found in our samples. Magnetic hysteresis-loops were obtained from the (Ga,Mn)N samples with SQUID magnetometer at 293 K.

This work is partly sponsored by National Natural Science Foundation of China under contract 60176001, the Ministry of Chinese National Science and Technology under contract PAN95-YU-34, Special Funds for Major State Basic Research Projects G20000683, G20000365 and G2002CB311905.

References

[1] T. Hayashi, M. Tanaka, T. Nishinaga, H. Shimada, J. Appl. Phys. 81 (1997) 4865.
[2] H. Ohno, H. Munekata, S. Molnar, L.L. Chang, J. Appl. Phys. 69 (1991) 6103.
[3] N. Karar, S. Basu, R. Venkatarghavan, B.M. Aror, J. Appl. Phys. 88 (2000) 924.
[4] H. Ohno, Science 281 (1998) 951.
[5] H. Ohno, Appl. Phys. Lett. 69 (1996) 363.
[6] N. Theodoropoulou, A.F. Hebard, Phys. Rev. Lett. 89 (2002) 107203.
[7] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani, Nature 408 (2000) 944.
[8] R. Fiederling, M. Keim, G. Reuscher, W. Ossau, G. Schmidt, A. Waag, L.W. Molenkamp, Nature 402 (1999) 787.
[9] Y. Ohno, D.K. Young, B. Beschoten, F. Matsukura, H. Ohno, D.D. Awschalom, Nature 402 (1999) 790.
[10] J. Konig, H.H. Lin, A.H. MacDonald, Phys. Rev. Lett. 84 (2000) 5628.
[11] T. Diehl, H. Ohno, F. Matsukura, J. Cibert, D. Ferrand, Science 287 (2000) 1019.
[12] N. Theodoropoulou, A.F. hebard, Appl. Phys. Lett. 78 (22) (2001) 3475.
[13] E. Kulatov, H. Nakayama, Phys. Rev. B 66 (2002) 045203.
[14] Yoon Shon, Young Hae Kwon, Deuk Young Kim, Xiangjun Fan, Dejun Fu, Tae Won Kang, Jpn. J. Appl. Phys. 40 (2001) 5304.