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Magnetic and electrical properties of zincblende CrAs*

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This paper reports that 9 nm zincblende CrAs is grown by molecular-beam epitaxy on InAs buffer layer. The zb-CrAs shows ferromagnetism at room temperature and the total magnetic moment $3.09 \pm 0.15\,\mu_{\rm B}$ per CrAs unit. The temperature dependence of zb-CrAs resistance R shows metallic behaviour.

Keywords: zincblende, molecular-beam epitaxy, half-metal
PACC: 7000, 7155D, 7200, 7430C

1. Introduction

The emerging field of spintronics[1,2] has provided a strong motivation towards the fabrication of novel magnetic materials. A strong interest has been focused on the so-called half-metallic ferromagnets, i.e. metallic compounds for which either the majority or minority spin-channel presents a gap at the Fermi level. It is expected that the fully spin-polarized ferromagnetic films improve the performance of spin-dependent devices like a spin filter and a spin injection pad.[3−8] A lot of half-metallic ferromagnets have been theoretically predicted and some of them furthermore have been confirmed experimentally.[9−12] In particular, researches on making a connection between magnetic materials and semiconductors are focused because of the high possibility of giving several devices. The development of a growth technique by molecular beam epitaxy (MBE) also has promoted an advance in epitaxial growth of magnetic thin films on semiconductor substrates. Novel half-metallic ferromagnets compatible with III–V semiconductors, i.e. zinc-blende structure MnAs, CrAs, and CrSb, have been designed theoretically on the basis of *ab initio* density-functional calculations.[13−15] These materials have been successfully grown on III–V semiconductors by MBE and they have been confirmed to exhibit ferromagnetic behaviour at room temperature.[16−18] The equilibrium crystal structure of MnAs, CrAs, and CrSb is of the NiAs type.[19] This structure does not lead to half-metallicity.[20−24] The zinc-blende (zb) structure can only be obtained by the epitaxial growth on semiconductors. Akinaga *et al*[16] grew CrAs on GaAs substrates and found CrAs to be a ferromagnet having a Curie temperature higher than 400 K. The experimental results were complemented by *ab initio* electronic structure calculations showing that the magnetic moment was $3\,\mu_{\rm B}$.

However, the critical thickness of zb-CrAs to maintain a continuous epitaxial relationship between GaAs is below 3 nm before.[16,25] When a thicker film than 3 nm was grown, an unrecognized pattern appeared in the reflection high-energy electron diffraction (RHEED). Many multilayers show a critical thickness of layer where a transition from the strained structure on substrate to a normal bulk structure occurs.[26,27] The stabilization and critical thickness of strained phase in these multilayers are thermodynamically considered.[28−30] The critical thickness 3 nm of zb-CrAs restricts the understanding and application of this new half-metallic material. In this work, we have increased the thickness of zb-CrAs layers to 9 nm on InAs buffers employing MBE, and study the magnetic and electrical properties of zb-CrAs. Galanakis concluded that zb-CrAs grown on InAs remains half metallic.[31]

2. Experimental details

Epitaxial growth of sample 1 with structure CrAs(9 nm)/InAs(800 nm)/ GaSb(500 nm)/AlSb

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(100 nm)/GaAs(50 nm) was performed in a MBE chamber on insulating GaAs (001) substrates. The complex template InAs(800 nm)/ GaSb(500 nm) /AlSb(100 nm)/GaAs(50 nm) was grown in order to become a zb structure InAs with smooth surface. Surface reconstruction was monitored by RHEED during growth. After desorption of the oxide layer on a GaAs substrate at $T_s = 580$°C, a 50 nm thick GaAs buffer layer was grown at 560°C. 100 nm AlSb and 500 nm GaSb were grown at $T_s = 540$°C, and the RHEED pattern transformed from streaky (2×4) to (1×3). 800 nm InAs was grown at $T_s = 430$°C. The RHEED pattern transformed from streaky (1×3) to (2×4), which indicates streaky (2×4) InAs with smooth surface. T_s was lowered to 210°C, and the substrate temperature T_s was kept at 210°C one hour. Then the CrAs was grown at 210°C with a growth rate of about 0.02 nm/s. Clear streaky (1×2) RHEED pattern was observed (Fig.1), and the symmetry of the intensity fluctuation shows the zb crystal structure. After 450 seconds, the streaky RHEED pattern shows an unknown phase and a twin-structure appeared, which indicates the critical thickness (about 9 nm) of the zb-CrAs thin film. The critical thickness (about 9 nm) of the zb-CrAs thin film grown on InAs is more than that (3 nm) of zb-CrAs thin film grown on GaAs.[16] The critical thickness enhancement of zb-CrAs should be related to the lattice mismatch between stable zb-CrAs and InAs or GaAs. According to consideration of the critical thickness in other multilayers, the smaller lattice mismatch between the stable phase and substrate leads to thicker strained phase.[28−30] The lattice constant of InAs is 0.605 nm, while the lattice constant of GaAs is 0.565 nm. It is theoretically predicted that zb-CrAs is stable with lattice constant about 0.585 nm. The lattice mismatch 3.41% between the stable zb-CrAs and InAs is smaller than that 3.54% between the stable zb-CrAs and GaAs, and zb-CrAs on InAs is more stable than that on GaAs.[15] In addition, the energetic increase of atoms by strain (zb-CrAs on InAs) is smaller than that by press (zb-CrAs on GaAs) due to the dissymmetrical potential function of atoms. So the critical thickness of zb-CrAs on InAs is larger than that of zb-CrAs on InAs. For comparison, sample 2 with structure InAs(800 nm)/ GaSb(500 nm)/AlSb (100 nm)/GaAs(50 nm) was grown in a MBE chamber on insulated GaAs (001) substrates.

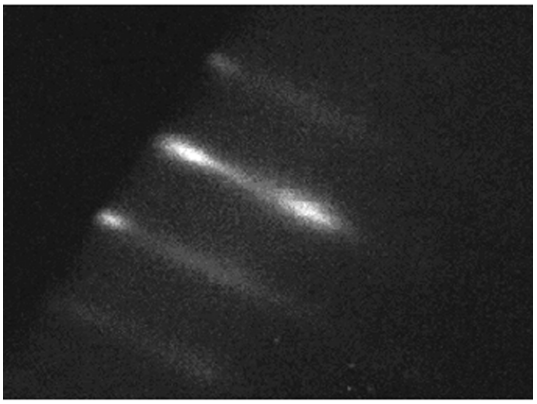


Fig.1. RHEED pattern of CrAs grown on InAs, which was taken with the electron-beam incidences along [110] GaAs directions.

3. Results and Discussion

Figure 2 presents the atomic force microscopy (AFM) image of sample 1. The surface of sample 1 is smooth except for holes and the average roughness is 3.2 nm, which is consistent with the streaky RHEED pattern of sample 1.

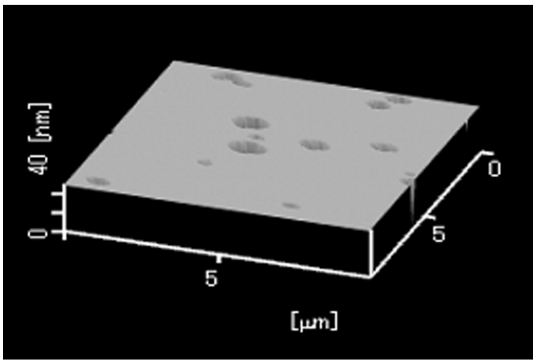


Fig.2. AFM image of CrAs grown on InAs.

Magnetization measurements of sample 1 were carried out by using a superconducting quantum interference device (SQUID) magnetometer. The magnetic field dependence of magnetization at 5 K and 300 K were shown in Fig.3. Saturation magnetization at 5 K (Fig.3) of the samples suggest the total magnetic moment $3.09 \pm 0.15\,\mu_B$ per CrAs unit, which agrees well with the theoretical prediction $3\mu_B$ and other experimental results.[16] The error bar of total magnetic moment is due to the area estimation uncertainty. The hysteresis loop at 300 K (Fig.3) shows clearly ferromagnetism at room temperature. The temperature dependence of magnetization (Inset of Fig.3) indicates

that the Curie temperature of CrAs is higher than 400 K. The coercive fields are 6400 A/m at 5 K and 4800 A/m at 300 K. The remanence is 6.2×10^{-5} emu at 5 K and 4.1×10^{-5} emu at 300 K. The magnetic properties of zb-CrAs on InAs are analogous to that of zb-CrAs on GaAs.

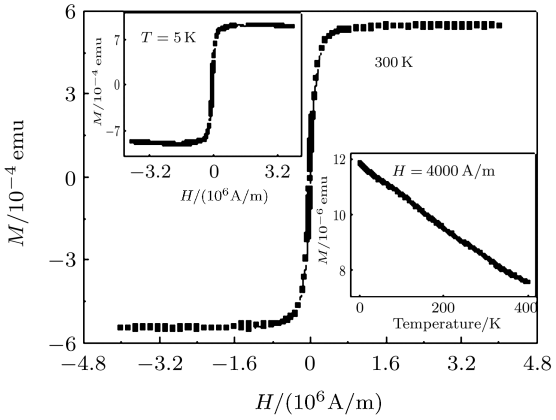


Fig.3. Magnetic field dependence of magnetization of CrAs grown on InAs at 300 K and 5 K. Inset shows the temperature dependence of magnetization under magnetic field 4000 A/m.

The resistance R was measured by using four points probes on the surface of sample. The temperature dependence of resistance R of sample 1 is shown in Fig.4. R increases with the increase of temperature from 5 K to 300 K, which indicates metal character of sample 1. For comparison, the temperature dependence of resistance R of sample 2 was shown in inset of Fig.4, in which R decreases with the increase of temperature from 5 K to 300 K. So the temperature dependent character of resistance R of sample 1 (Fig.4) is due to zb-CrAs layer. That is to say, zb-CrAs shows metallic behaviour. The usual expression for the temperature dependence of resistance for metals and alloys can be described by the Matthiessen rule $R(T) = R_0 + CT^n$. A plot of $\ln(R - R_0)$ as a function of $\ln(T)$ will yield the power-law parameter n (Fig.5). For temperature $T < 50$ K, the resistivity behaves according to R–$T^{2.2}$ power law. It is known that, in the case of ferromagnetic elements such as Fe, Co and Ni, the resistivity usually has a term proportional to T^2 at low temperature, which is ascribed to inelastic electron-phonon scattering from vibrating impurities. Above 200 K, the resistivity dependence transforms from $T^{2.2}$ dependence to an almost purely phononic linear dependence $n = 0.93$.

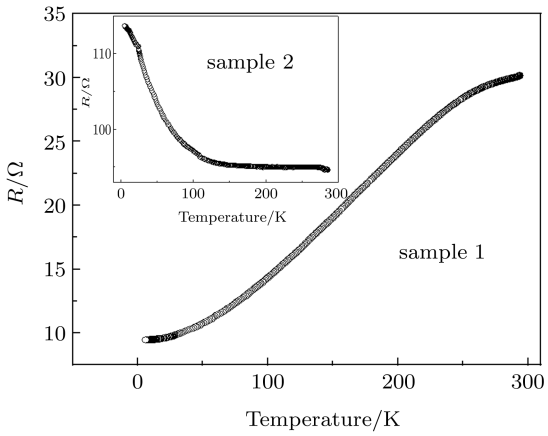


Fig.4. Temperature dependence of electrical resistance for sample 1. Inset shows the temperature dependence of electrical resistance for sample 2.

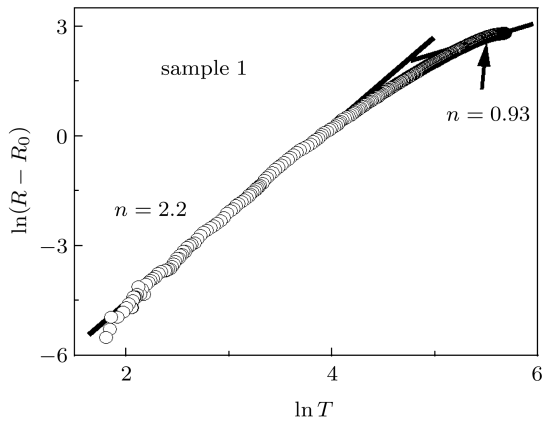


Fig.5. $\ln(R - R_0)$ as a function of $\ln(T)$ for sample 1 resistance data. The slope of this curve corresponds to the power-law exponent n if we assume the functional form $R(T) = R_0 + CT^n$.

4. Conclusion

We have grown 9 nm zb-CrAs on InAs, which is thicker than reported critical thickness 3 nm of zb-CrAs on GaAs.[16] The zb-CrAs shows ferromagnetism at room temperature and the total magnetic moment $3.09 \pm 0.15\,\mu_B$ per CrAs unit. The temperature dependence of zb-CrAs resistance R shows metallic behaviour.

References

[1] Prinz G A 1998 *Science* **282** 1660

[2] de Boeck J, van Roy W, Das J, Motsnyi V, Liu Z, Lagae L, Boeve H, Dessein K and Borghs G 2002 *Semicond. Sci. Technol.* **17** 342

[3] de Groot R A, Mueller F M, van Engen P G and Buschow K H J 1983 *Phys. Rev. Lett.* **50** 2024

[4] Sun J Z, Gallagher W J, Duncombe P R, Krusin-Elbaum L, Altman R A, Gupta A, Yu L, Gong G Q and Xiao G 1996 *Appl. Phys. Lett.* **69** 3266

[5] Park J H, Vescovo E, Kim H J, Kwon C, Ramesh R and Venkatesan T 1998 *Nature* **392** 794

[6] Soulen R J, M Byers J, Osofsky M S, Nadgorhy B, Ambrose T, Cheng S F, Broussard P R, Tanaka C T, Nowak J, Moodera J S, Barry A and Coey J M 1998 *Science* **282** 82

[7] Borca C N, Komesu T, Jeong H, Dowben P A, Ristoiu D, Hordequin C, Pierre J and Nozieres J P 2000 *Appl. Phys. Lett.* **77** 88

[8] Brener N E, Tyler J M, Callaway J, Bagayoko D and Zhao G L 2000 *Phys. Rev.* B **61** 16582

[9] Soulen R J, Byers J M, Osofsky M S, Nadgorny B, Ambrose T, Cheng S F, Broussard P R, Tanaka C T, Nowak J, Moodera J S, Barry A and Coey J M D 1998 *Science* **282** 85

[10] Schwarz K 1986 *J. Phys.* F: *Met. Phys.* **16** L211
Korotin M A, Anisimov V I, Khomskii D I and Sawatzky G A 1998 *Phys. Rev. Lett.* **80** 4305

[11] Yanase A and Siratori K 1984 *J. Phys. Soc. Jpn.* **53** 312

[12] Galanakis I, Dederichs P H and Papanikolaou N 2002 *Phys. Rev.* B **66** 134428

[13] Shirai M, Ogawa T, Kitagawa I and Suzuki N 1988 *J. Magn. Magn. Mater.* **177–181** 1383

[14] Shirai M 2001 *Physica* E **10** 143

[15] Shirai M 2003 *J. Appl. Phys.* **93** 6844

[16] Akinaga H, Manago T and Shirai M 2000 *Japan. J. Appl. Phys.* **39** L1118
Bi J F, Deng J J, Ji Y, Li S S, Lu J, Wang W Z, Zhao J H and Zheng Y H 2007 *Chin. Phys.* **16** 3868

[17] Zhao J H, Matsukura F, Takamura K, Abe E, Chiba D and Ohno H 2001 *Appl. Phys. Lett.* **79** 2776
Etgens V H 2004 *Phys. Rev. Lett.* **92** 167205-1
Akinaga H and Mizuguchi M 2004 *J. Phys.*: *Cond. Matter* **16** s5549

[18] Ono K, Okabayashi J, Mizuguchi M, Oshima M, Fujimori A and Akinaga H 2002 *J. Appl. Phys.* **91** 8088
Chioncel L 2005 *Phys. Rev.* B **71** 085111
J F Bi *et al* 2006 *Appl. Phys. Lett.* **88** 142509

[19] Landolt-Börnstein 1988 *New Series* Group III **27** (Part A edited by K Adachi and S Ogawa) (Heidelberg: Springer)

[20] Wei S H and Zunger A 1987 *Phys. Rev.* B **35** 2340

[21] Sanvito S and Hill N A 2000 *Phys. Rev.* B **62** 15553

[22] Continenza A, Picozzi S, Geng W T and Freeman A J 2001 *Phys. Rev.* B **64** 085204

[23] Zhao Y J, Geng W T, Freeman A J and Delley B 2002 *Phys. Rev.* B **65** 113202

[24] Xie W H, Xu Y Q, Liu B G and Pettifor D G 2003 *Phys. Rev. Lett.* **91** 037204

[25] Mizuguchi M, Akinaga H and Manago T 2002 *J. Appl. Phys.* **91** 7917

[26] Banerjee R, Ahuja R and Fraser H L 1996 *Phys. Rev. Lett.* **76** 3778
Jankowski A and Wall Mark A 1994 *J. Mater. Res.* **9** 31

[27] Rizzi G A, Petukhov M, Sambi M and Granozzi G 2003 *Surf. Sci.* **522** 1

[28] Li J C, Liu W and Jiang Q 2005 *Appl. Surf. Sci.* **239** 259

[29] Thompson G B, Banerjee R and Fraser H L 2004 *Appl. Phys. Lett.* **84** 1082

[30] Dregia S A, Banerjee R and Fraser H L 1998 *Scripta Materialia* **39** 217

[31] Galanakis I 2002 *Phys. Rev.* B **66** 012406