

Atomic level characterization of heterostructures by X-ray CTR scattering

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In the identification of crystal structure of ErP, X-ray CTR (crystal truncation rod) scattering measurement played a definitive role and it was revealed that ErP keeps its original crystal structure as the rocksalt even in the several monolayer (ML) thicknesses. This fact led us to measure the quantum-size effects on the energy gap, i.e., semimetal to semiconductor transition. In this paper we describe the principle of the X-ray CTR scattering, measurement system, and several results of the measurement and analysis.

The X-ray CTR scattering is based on the Laue function of which shape has a widely spread tails on both sides of the Bragg point due to finite penetration depth of X-ray from the crystal surface. The majority part of the crystal causes the high intensity Bragg point (diffraction) and the surface and/or heterostructure (both are different from the majority part of the crystal) largely modifies the tail part of the Laue function. This modification enables us to deduce the surface structure and heterostructure in the atomic level. Since the intensity of the tail parts is by 5-6 orders of magnitude lower than that of Bragg point (roughly proportional to the number of unit cells), a very high intensity of X-ray source and a high sensitivity detector with a wide dynamic range are necessary. We have been using synchrotron radiation as the X-ray source and the imaging plate (IP) as the detector.

The sample for the measurement was grown on InP (001) at 530°C by organometallic vapor phase epitaxy using TMI_n, TBP and (MeCp)₃Er as the source materials. The layer structure was designed to be InP cap(100Å)/ErP(0.2ML)/InP buffer(1000Å)/InP substrate.

In the analysis of the measured spectrum of the X-ray CTR scattering, the rocksalt structure, Er atoms substituting the In sites, Er atoms being on the Td site with P atoms nearest, and Er atoms being on the Td site with In atoms nearest were assumed as the crystal structure of ErP (location of Er atoms). Only the rocksalt structure fit the measured spectrum of the CTR scattering. The obtained parameters of the layer structure were 30ML (88Å) of the InP cap layer and 0.171 ML of the ErP layer. The Er atoms distributed as the Gaussian function with the peak of 0.032ML and the half width of 5ML. In reality, the STM observation revealed that ErP is grown as nanometer scale islands with different heights. The X-ray CTR scattering is insensitive to the lateral distribution of the thickness (height of the islands from 0 to several ML) but gives a definitive information of the crystal structure and the thickness of the layer.

The same technique was applied to the heterostructure of InP/GaInAs(3ML)/InP grown by 3 different growth process to obtain the sharpest interface of InP/GaInAs [1]. It revealed that a long purge time (13s) or an additional supply of Ga and In after growth of GaInAs gave a sharpest interfaces as intended, but at the same time unexpectedly wide distribution of Ga was observed.

[1] M. Tabuchi, R. Takahashi, M. Araki, K. Hirayama, N. Futakuchi, Y. Shimogaki, Y. Nakano and Y. Takeda: *Appl. Surf. Sci.*, **159-160**, 250 (2000).

(1) Publications

- 1) Y. Fujiwara, T. Ito, H. Ofuchi, T. Kawamoto, M. Tabuchi and Y. Takeda : "High thermal stability of Er-related luminescence and atom configurations around Er atoms doped in InP by OMVPE growth" Institute of Physics Conference Series, No. 162, pp. 173-176 (1999).
- 2) H. Ofuchi, T. Ito, T. Kawamoto, M. Tabuchi, Y. Fujiwara and Y. Takeda: "Thermal stability of atom configurations around Er atoms doped in InP by OMVPE" Japanese Journal of Applied Physics, Vol. 38, Suppl. 38-1, pp. 542-544 (1999).
- 3) H. Ofuchi, T. Kubo, M. Tabuchi, K. Takahei and Y. Takeda: "Fluorescence EXAFS study on low dimensional structures around Er atoms in GaAs:Er,O" 3rd International Conference on Low Dimensional Structures and Devices, Antalya, Turkey, 182, September 15-17 (1999).
- 4) Y. Hamanaka, A. Nakamura, S. Omi, N. Del Fatti, F. Vallee, C. Flytzanis: "Ultrafast response of nonlinear refractive index of silver nanocrystals embedded in glass" Applied Physics letters, Vol.75, pp.1712-1714 (1999)
- 5) Y. Fujiwara, T. Itoh, M. Ichida, T. Kawamoto, O. Watanabe, I. Yamanaka, A. Nakamura and Y. Takeda, "Thermal quenching of Er-related luminescence in GaInP doped with Er by organometallic vapor phase epitaxy" ,Japanese Journal of Applied Physics, Vol. 38, pp. 1008-1011 (1999).
- 6) Y. Fujiwara, T. Ito, M. Ichida, T. Kawamoto, O. Watanabe, I. Yamakawa, A. Nakamura and Y. Takeda: "Relaxation of optically excited 4f electrons in Er-doped Ga_xIn_{1-x}P", Physica B, Vol. 272, pp. 428-430 (1999)
- 7) Y. Fujiwara, T. Kawamoto, T. Koide and Y. Takeda: "Luminescence properties of Er,O-codoped III-V semiconductors grown by organometallic vapor phase epitaxy", Physica B, Vols. 273-274, pp. 770-773 (1999).
- 8) Y. Fujiwara, T. Kawamoto, M. Ichida, S. Fuchi, Y. Nonogaki, A. Nakamura and Y. Takeda: "Er-related luminescence from self-assembled InAs quantum dots doped with Er by organometallic vapor phase epitaxy", Journal of Luminescence, Vols. 87-89, pp. 326-329 (2000).
- 9) Y. Fujiwara, T. Koide and Y. Takeda (Invited): "Luminescence properties of Er,O-codoped GaP grown by organometallic vapor phase epitaxy", E-MRS Spring 2000 Meeting, Symposium K: Rare Earth Doped Semiconductors III, Strasbourg, France, #0294, May 30-June 2 (2000).
- 10) T. Koide, Y. Fujiwara and Y. Takeda: "OMVPE growth and properties of Dy-doped III-V semiconductors", International Conference on the Physics and Application of Spin-Related Phenomena in Semiconductors, Sendai, Japan, September 13-15 (2000).
- 11) A. Koizumi, H. Moriya, N. Watanabe, Y. Nonogaki, Y. Fujiwara and Y. Takeda: "Luminescence properties of Er,O-codoped InGaAs/GaAs MQW structures grown by organometallic vapor phase epitaxy", 25th International Conference on the Physics of Semiconductors, Osaka, Japan, O33, September 17-22 (2000).
- 12) Y. Fujiwara, H. Ofuchi, M. Tabuchi and Y. Takeda: "Growth condition dependences of optical properties of Er in InP and local structures", InP and Related Compounds, Chapter 7, Ed., M.O. Manasreh (Gordon and Breach, Amsterdam, 2000).
- 13) Y. Takeda and M. Tabuchi: "Monolayer scale analysis of heterostructures and interfaces by X-ray CTR scattering and interference", InP and Related Compounds, Chapter 10, Ed., M.O. Manasreh (Gordon and Breach, Amsterdam, 2000).
- 14) H. Ofuchi, T. Kubo, M. Tabuchi, K. Takahei and Y. Takeda : "Local structures around Er atoms in GaAs:Er,O studied by fluorescence EXAFS and photoluminescence", Microelectronic Engineering, Vols. 51-52, pp.715-721 (2000) .

- 15) N. Del Fatti, F. Vallee, C. Flytzanis, Y. Hamanaka and A. Nakamura: "Electron dynamics and surface plasmon resonance nonlinearities in metal nanoparticles" *Chemical Physics*, Vol. 251, pp.215-226 (2000).
- 16) Y. Hamanaka, J. Kuwabata, A. Nakamura, I. Tanahashi and S. Omi: "Electron energy relaxation dependent on size and matrix in gold nanocrystal-dielectric composites" *Proceedings of International Conference on Ultrafast Phenomena* (2000).
- 17) Y. Hamanaka, J. Kuwabata, A. Nakamura, I. Tanahashi and S. Omi: "Ultrafast electron relaxation via breathing vibration of gold nanocrystals embedded in a dielectric medium", submitted to *Phys. Rev.*
- 18) T. Yamauchi, Y. Matsuba, L. Bolotov, M. Taguchi and A. Nakamura: "A correlation between a gap energy and a size of single InAs quantum dots on GaAs(001) studied by scanning tunneling spectroscopy", to appear in *Appl. Phys. Lett.*
- 19) T. Yamauchi, Y. Matsuba, Y. Ohyama, M. Taguchi and A. Nakamura: "Quantum size effects of InAs- and InGaAs-single quantum dots studied by scanning tunneling microscopy/spectroscopy", submitted to *Jpn. J. Appl. Phys.*
- 20) J. Inoue, S. Nonoyama and H. Itoh: "Double resonance mechanism of ferromagnetism and magneto-transport in (Ga-Mn)As", *Phys. Rev. Lett.* to be published
- 21) J. Inoue, S. Nonoyama and H. Itoh: "Ferromagnetism and spin-dependent transport in magnetic semiconductors", *Physica E*, to be published
- 22) S. Nonoyama and J. Inoue: "Spin dependent resonant tunneling in magnetic semiconductors", *Physica E*, to be published

(2) Presentations

- 1) 小出辰彦、川本武司、藤原康文、竹田美和:「OMVPE法によるIII-V族化合物半導体へのEr,O共添加(II)」, 第60回応用物理学学会学術講演会、3p-ZF-16、甲南大学、神戸市東灘区、9月1日-4日(1999).
- 2) 桑畑順也、濱中泰、中村新男、棚橋一郎、近江成明:「Auナノ結晶のサイズとマトリックスに依存した非線形光学応答」、1999年日本物理学会秋の分科会、講演概要集、第54巻第2号、p.683、岩手大学、盛岡、9月
- 3) 桑畑順也、濱中泰、中村新男、棚橋一郎、近江成明:「Auナノ結晶のサイズとマトリックスに依存した非線形光学応答II」、2000年日本物理学会春の分科会、講演概要集、第55巻第2号、p.647、関西大学、吹田、3月
- 4) 小泉淳、守屋博光、渡邊直樹、野々垣陽一、藤原康文、竹田美和:「減圧OMVPE法による $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ MQW構造中へのEr,O共添加」、第47回応用物理学関係連合講演会、28a-ZG-4、青山学院大学、東京都渋谷区、3月28日-31日(2000).
- 5) 小出辰彦、磯貝佳孝、藤原康文、竹田美和:「OMVPE法によるIII-V族半導体へのDy添加」、第47回応用物理学関係連合講演会、28a-ZG-6、青山学院大学、東京都渋谷区、3月28日-31日(2000).
- 6) 小泉淳、守屋博光、渡邊直樹、野々垣陽一、藤原康文、竹田美和:「減圧OMVPE法による $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ MQW構造中へのEr,O共添加と発光特性」、第61回応用物理学学術講演会、5p-W-10、北海道工業大学、札幌市手稲区、9月3日-7日(2000).
- 7) 小出辰彦、磯貝佳孝、藤原康文、竹田美和:「OMVPE法によるIII-V族半導体へのDy添加と光学的特性」、第61回応用物理学学術講演会、5p-W-11、北海道工業大学、札幌市手稲区、9月3日-7日(2000).

(3) Patent application 1 file