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QUANTUM NANOSTRUCTURES

by Droplet Epitaxy

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ABSTRACT

Droplet epitaxy is an alternative growth technique for several quantum nanostructures. Indium droplets are distributed randomly on GaAs substrates at low temperatures (120-350℃). Under background pressure of group V elements, Arsenic and Phosphorous, InAs and InP nanostructures are created. Quantum rings with isotropic shape are obtained at low temperature range. When the growth thickness is increased, quantum rings are transformed to quantum dot rings. At high temperature range, anisotropic strain gives rise to quantum rings with square holes and non-uniform ring stripe. Regrowth of quantum dots on these anisotropic quantum rings, Quadra-Quantum Dots (QQDs) could be realized. Potential applications of these quantum nanostructures are also discussed.

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I. Introduction

Surface tension of lotus leaves gives water droplets on their surfaces. This phenomenon is based on the nanostructure of upper-most layer of lotus leaves. Similar behavior could be formulated by spraying atomic beams onto substrates with different lattice constants. This growth technique is called "Droplet Epitaxy" [1] which could be operated in molecular beam epitaxy (MBE) machine under ultra-high vacuum condition.

Indium droplets could be distributed onto GaAs substrates at low temperature (120-350℃). Under Arsenic pressure at later processing step, different InAs nanostructures could be formulated at some controlled growth parameters such as substrate temperature, growth thickness and growth rate. Structure deformation of droplets during growth process is originated from strain field leading to atomic movement on the interface of materials having different lattice constants. Isotropic strain gives rise to quantum rings (QRs) having circular and uniform ring dimension.[2] At some critical thickness, localized strains on the ring induce the quantum dot formation on the ring stripe. Quantum rings are then transformed to quantum dot rings (QDRs).[3]

At higher growth temperature, out-diffusion of underneath substrate materials result in deep holes in the middle of quantum rings. In addition, anisotropic strain field becomes more influential to the structural deformation of quantum rings. The ring shape becomes anisotropic configuration having non-uniform ring stripe. The holes in the middle of quantum rings are transformed into square shape which is preferable in being used as nano-templates for quadra-quantum dots (QQDs). These QQDs are ideal quantum dot sets for quantum cellular antomata (QCA)[4] application which is one of the concepts in quantum computation. In this presentation, we introduce the "Droplet Epitaxy" growth technique in preparing different quantum nanostructures from different semiconductor materials, i.e. InAs, InGaAs and InP on GaAs substrates.

II. Droplet Epitaxy for Quantum Nanostructures

Self-assembled quantum nanostructures are normally grown by S-K growth mode in MBE system based on strain relaxation process.[5] InAs/GaAs system is a typical example of defects-free quantum dot structure due to lattice mismatch of 7% of this matrix. Typical growth temperature of this conventional MBE growth technique is around 500℃ with Indium beam-shutter opened under Arsenic background pressure in the MBE growth chamber. InAs epitaxial layer is then grown onto the lattice-mismatched GaAs buffer layer until the InAs thickness reaches critical value of strain. Then, strain relaxation mechanism works and creates InAs quantum dots on the wetting layer as shown by AFM image in figure 1. These quantum dots are distributed randomly by nature. They are defect-free nanocrystal providing good electronic and optical properties. Quantum dots are, therefore, potential active part of nanoelectronic and nanophotonic devices such as QD lasers,[6] QD single electron devices,[7] QD solar cells.[8]

In order to create other kinds of quantum nanostructures, new approaches of growth techniques are invented. Among several of them, "Droplet Epitaxy" is selected to be investigated in our work. Droplet epitaxy could be easily operated in MBE machine at rather low growth temperature (120-350℃). Indium droplet s are sprayed on the GaAs substrate at the beginning step. Later on, Arsenic source is opened and then mixed with Indium droplets to form InAs different nanostructures depending on the deformation of original droplets under various growth conditions.

Due to out-diffusion of Indium atoms from the center of droplets, InAs quantum rings (QRs) are obtained as shown in figure 2. As the growth thickness is further increased, localized strain on the ring stripe becomes strong enough to induce many quantum dots on the ring structure. Quantum dot rings (QDRs) could be realized as shown in figure 3.

At higher growth temperature for droplet epitaxy, out-diffusion of Indium atoms from the center of droplets occurs under anisotropic strain. The ring stripe of quantum rings becomes non-uniform and the nano-holes are deep and have square-shape as shown in figure 4. Using these peculiar QRs as templates, 4 QDs situating at each corner of square shape are regrown (see figure 5). Two of these QDs are aligned either $[1\bar{1}0]$ or $[110]$ which are preferrable crystallo-graphic directions of QD alignment in general.

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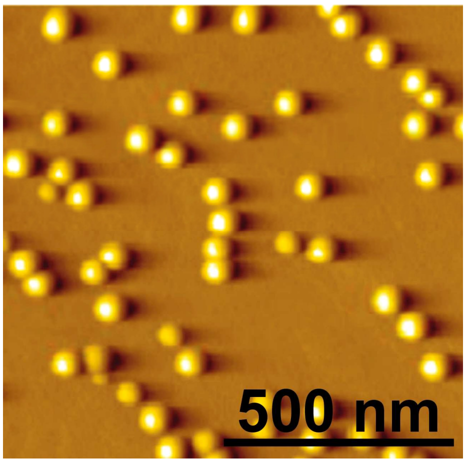

Figure 1
Self-assembled quantum dots grown by S-K growth mode in MBE machine

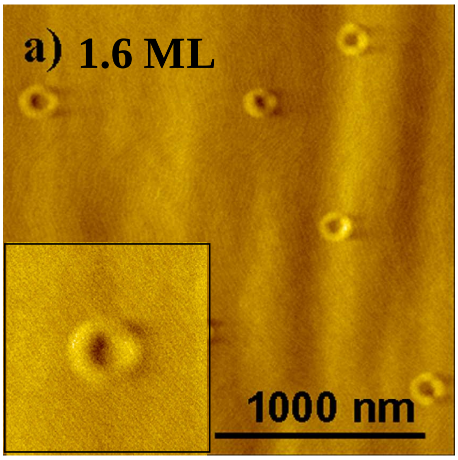

Figure 2
Quantum Rings (QRs) by droplet epitaxy at growth temperature of 250°C and droplet thickness of 1.6 ML

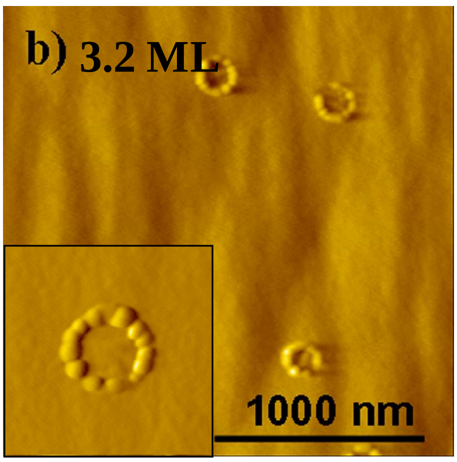

Figure 3
Quantum Dot Rings (QDRs) are also obtained by droplet epitaxy at droplet thickness of 3.2 ML

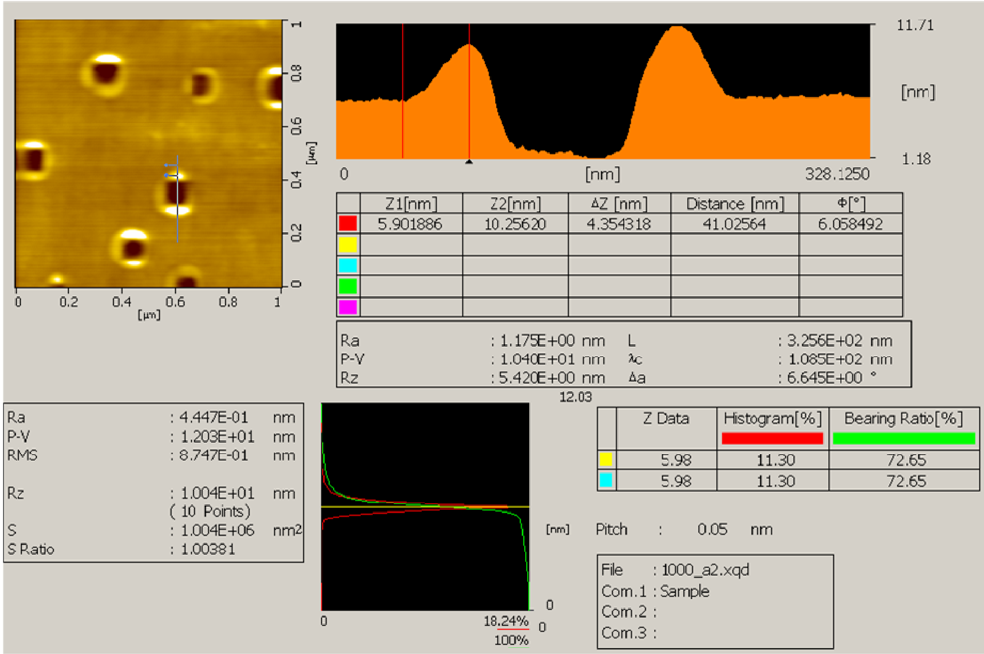

Figure 4
QRs with square-shape nanoholes

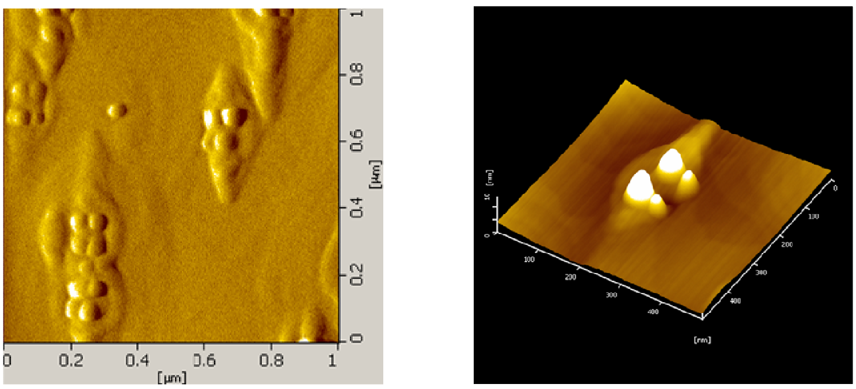

Figure 5
4 QDs at the corners of square configuration

III. Potential Applications of Quantum Nanostructures Grown by Droplet Epitaxy

QRs and QDRs have ring-shape which would be applicable for memory devices based on persistant current induced by external electric or magnetic fields. Adding some ferromagnetic elements in the ring structure would enlarge the signals and their reliabity. Quantum nanostructures made from magnetic semiconductor materials would be another interesting research topics in our group.

QD set having 4 QDs, one QD at each corner of a square, would be a basic element for quantum cellular automata (QCA) which is one of the principles for future quantum computation. Figure 6 illustrates an idea of logic gate using combination of QD sets which need some cross-over and some alignments of QD sets. We also demonstrate how to grow QDs with alignments on both $[1\bar{1}0]$ or $[110]$ directions as well as cross-over by using cross-hatched substrates as shown in figure 7.

In order to fabricate practical quantum dots with particular patterns for QCA, self-assembly approach alone is not sufficient to perfect the devices. Combination of top-down and bottom-up growth techniques would be investigated. Nanolithography would be developed as primary step prior to QD growth.

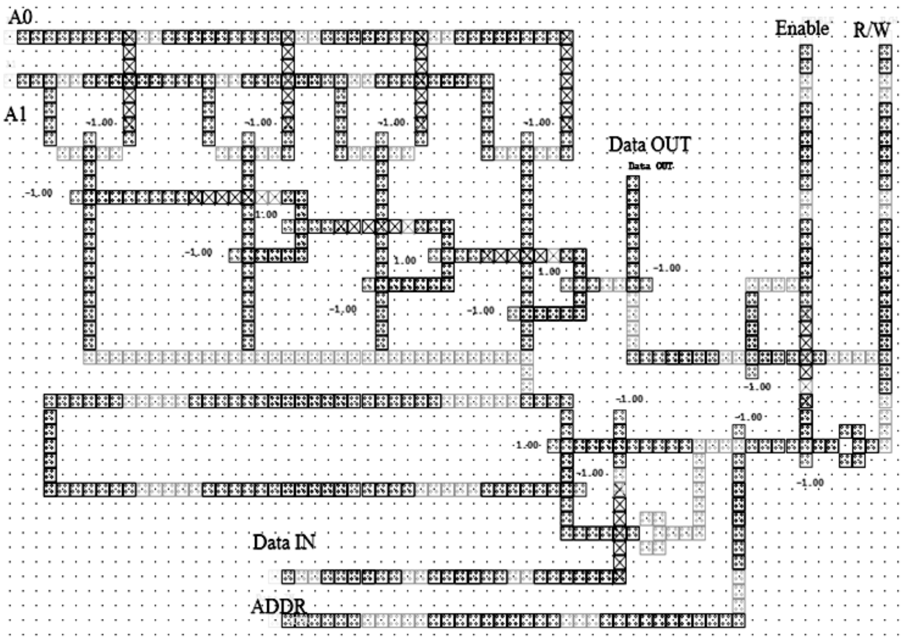

Figure 6
Logic gate operated by QCA principle

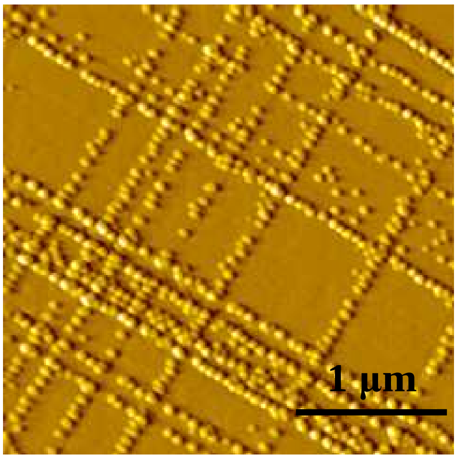

Figure 7
QDs grown on cross-hatched substrates

IV. Summary

"Droplet Epitaxy" has been developed and used to grow different types of quantum nanostructures, such as quantum rings, quantum dot rings as well as a nano-templates for Quadra-Quantum Dots which are used as a basic cell in quantum cellular automata. Droplet epitaxy is an alternative MBE growth technique which is operated at lower temperatures than conventional S-K growth mode. With Indium droplets at the beginning and background pressure of group V elements at the later step, InAs, InP nanostructures could be created.

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REFERENCES

[1] J. H. Lee, Z. M. Wang, N. W. Strom, Y. I. Mazur, and G. J. Salamo, "InGaAs quantum dot molecules around self-assembled GaAs nanomound templates," *Applied Physics Letters*, vol. 89, pp. 202101-3, 2006.

[2] N. Pankaow, S. Panyakeow, and S. Ratanathammaphan, "Nanometer-scale In0.5Ga0.5As ring-like structure grown by droplet epitaxy," *Advanced Materials Research*, vol. 31 (2008), pp. 123-125, 2008.

[3] W. Jevasuwan, S. Panyakeow, and S. Ratanathammaphan, "in-droplet-induced formation of InP nanostructures by solid-source molecular-beam epitaxy," *Microelectronic Engineering, Proceedings of the 32nd International Conference on Micro- and Nano-Engineering*, vol. 84, pp. 1548-1551, 2007.

[4] J. Timler and C. S. Lent, "Power gain and dissipation in quantum-dot cellular automata," *Journal of Applied Physics*, vol. 91, pp. 823-831, 2002.

[5] A. G. Cullis, D. J. Norris, T. Walther, M. A. Migliorato, and M. Hopkinson, "Stranski-Krastanow transition and epitaxial island growth," *Physical Review B*, vol. 66, pp. 081305, 2002.

[6] Y. Arakawa and H. Sakaki, "Multidimensional quantum well laser and temperature dependence of its threshold current," *Applied Physics Letters*, vol. 40, pp. 939-941, 1982.

[7] S. S. Li, J. B. Xia, J. L. Liu, F. H. Yang, Z. C. Niu, S. L. Feng, and H. Z. Zheng, "InAs/GaAs single-electron quantum dot qubit," *Journal of Applied Physics*, vol. 90, pp. 6151-6155, 2001.

[8] S. Suraprapapich, S. Thainoi, S. Kanjanachuchai, and S. Panyakeow, "Quantum dot integration in heterostructure solar cells," *Solar Energy Materials and Solar Cells 14th International Photovoltaic Science and Engineering Conference*, vol. 90, pp. 2968-2974, 2006.