行政院國家科學委員會專題研究計畫成果報告

三五族半導體量子點結構之物理與元件

Studies of Quantum Dot Structure and Devices on III-V Compound Semiconductors

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主持人：李建平　　國立交通大學電子工程學系

一、中文摘要

我們使用分子束磊晶在(111)B的砷化鎵基板，發展出一套製造高品質量子點的方法。這種方法僅需調整磊晶成長的溫度，與應變誘導自組量子點成長法的應變機制無關，所得的量子點均勻度亦較高。經由原子力顯微鏡(AFM)量得的影像，以及光激光(PL)量測所得的波長偏移，證實了量子點的形成。而PL光譜所得的7.7meV線寬(Fig.1)顯示出量子點極佳的均勻度與非常優良的品質。同時我們也研究了成長厚度對量子點的影響(Fig.2)。

此外，我們還做了磁光譜的量測，分別在Farady及Voigt方向高達45Telsa的磁場下量測PL。比較量子井和量子點光譜的偏移可得知量子點具有較高的局限能量。而經由量得之數據估計載子波函數的空間分佈距離，與AFM影像所得的結果吻合。

關鍵詞：分子束磊晶、量子點、國科會

Abstract

We present a simple in situ method to fabricate high-quality InGaAs/GaAs quantum dots on (111)B GaAs substrates. The mechanism of the quantum dot formation is not strain relaxation but the growth characteristic of (111)B GaAs under low substrate temperatures. When the growth is performed at low temperatures, the layer-by-layer growth mode is replaced by island growth and therefore quantum dots are formed. The formation of the quantum dots was verified by atomic force microscope (AFM) images and the shift of photoluminescence (PL). The PL emission from the quantum dots was very strong and the full-width at half-maximum (FWHM) of the emission peak was as small as 7.7 meV(Fig.1), indicating excellent quality and very uniform dot formation. The effect of nominal thickness on the quantum dot formation has been investigated.(Fig.2)

We also report photoluminescence measurements on $In_{0.25}Ga_{0.75}As$/GaAs quantum well and dots grown on (111)B GaAs substrate in high magnetic fields up to 45 Tesla. A well-defined PL line with full width at half maximum of approximately 5.5 meV is observed. From an analysis of the zero field transition energy, we point out the importance of an internal piezoelectric field. By analyzing of the diamagnetic shift of the PL in both Faraday and Voigt configuration, the optical characteristics of a quasi-zero dimensional exciton are discussed.

Besides, we report a magneto optical characterization of the InGaAs/GaAs quantum well (QW) and quantum dot (QD) structures grown on (111)B GaAs substrate. The photoluminescence (PL) peak shift at high excitation condition is used in distinguishing QW from QD structure in addition to the atomic force microscopy (AFM) image. The binding energy in InGaAs/GaAs QW in (111)B direction is about 1 meV. The extent of the wave function obtained from the diamagnetic shift of the PL peak energy is consistent with the result

calculated by the k·p method. The InGaAs/GaAs QD lateral confine energy and the dots size are also estimated from diamagnetic shift of the PL lines. The lateral confine energy is 6 meV. The mean radii of the InGaAs QD is about 17 nm and the dot height is about 7 nm, which is in good agreement with the result as revealed in AFM image.

Keywords: Research Project, Report Style, National Science Council

二、計畫緣由與目的

Because of the advances in semiconductor epitaxial technology and process technology, devices based on quantum phenomena have recently been extensively explored. Due to the small effective mass and high dielectric constant, the quantum mechanical effects, which are normally seen in the atomic scale, are easily observable in semiconductor structures with dimensions of tens or hundreds of angstroms. The quantum mechanical effects combined with the optical properties of III-V heterostructures open up a whole new area for devices applications. Just to name a few: quantum well lasers, quantum well infrared detectors, and quantum well modulators. These devices have all been proved to be useful or potential useful for future electronic systems.

Magneto-optics in high magnetic fields is a powerful tool to investigate the electronic states in low-dimensional system. We could perform the magneto-photoluminescence (PL) measurement on InGaAs/GaAs QW and QD structures on (111)B substrate in magnetic fields up to 45 Tesla. From the high excitation-intensity PL spectra, the structure of the sample could be categorized as QW or QD and the lateral sizes and the heights of the dots could also be estimated from the spatial extents of the carrier wave functions (ECWFs).

三、結果與討論

It is known that epitaxial growth on GaAs (111)B substrates is difficult.[1] In order to obtain layer-by-layer growth by molecular beam epitaxy (MBE), the substrate temperature and the V/III ratio should be maintained at a certain level so that the surface reconstruction is $\sqrt{19}\times\sqrt{19}$.[2] If the substrate temperature drops below 500 , the surface reconstruction changes to 2×2 and the growth results in pyramids and twins.[3] This growth characteristic, however, was found to be useful in quantum dot formation. It has been reported that the 2×2 surface reconstruction is an As rich condition with many As trimers on top of the As surface layer.[4] During growth, it is difficult for incoming Ga atoms to bond to surface As atoms by breaking the connection between As trimers and the surface atoms.[5] Therefore, layer-by-layer growth is hindered and island growth is promoted. Therefore, if the growth proceeds in this manner, islands are formed. In this study, we found that when a very thin layer is grown under 2×2 surface reconstruction, small coherent quantum-size islands are formed.

One of the most commonly used methods in quantum dot fabrication is the so-called "self-assembled dot" (SAD) method using the Stranski-Krastanov growth mode. This method utilizes strain relaxation between two materials with large lattice mismatch to facilitate island growth and therefore quantum dots formation. Experimental results of SAD on substrates of (100) and (111)B GaAs have been reported.[6-8] However, the control of growth condition is critical for good uniformity of quantum dots. In our work, the mechanism of the quantum dot formation is not strain relaxation but the growth characteristic of (111)B GaAs under low substrate temperatures. We found that when the growth is performed at low temperatures, the layer-by-layer growth mode is replaced by island growth. The formation of the quantum dots was verified by atomic force microscopy (AFM) images and the shift of photoluminescence (PL). The full-width at half-maximum (FWHM) of the emission peak of the dots was as small as 7.7 meV, indicating very uniform dot formation.

In the magneto- PL measurements, InGaAs/GaAs QWs and QDs grown on (111)B GaAs substrate by varying the growing temperature from 525 to 450 °C were used. We have used magneto-optics in high magnetic fields to investigate the InGaAs/GaAs QWs and QDs grown on (111)B GaAs substrate at different growing temperature. The InGaAs/GaAs QW binding energy can be obtained by the diamagnetic shift and is about 1 meV. In addition, the ECWFs are also deduced from the diamagnetic shift. The in- plane ECWFs changed from 18.7 to 16.7 nm when the growing temperature varied from 525 to 450 °C. The in- plane ECWFs in QDs are slightly smaller than that in QWs because the weak confinement of the wider lateral size of the dots. The ECWFs in QWs in the growth direction obtained by diamagnetic shift are consistent with which calculated by k.p theory. The ECWFs in the z direction decreased from 525 to 480 °C and reached the minimum at 480 °C, the temperature which QD structure began to form, then increased as temperature goes down to 450 °C. The lateral size of the dot formed at growing temperature 480 °C is wider but its height is thinner. The lateral size becomes narrower but the height becomes thicker as the growing temperature is lowered to 450 °C.

四、計畫成果自評

In our research, optical characteristics of InGaAs/GaAs quantum dots on (111)B GaAs substrates fabricated by a new method were studied by photoluminescence. Island formation was clearly shown by AFM images. A PL linewidth of 7.7 meV at 8 K is obtained, which is the narrowest reported for quantum dots. The quality was excellent when the nominal thickness was not greater than 2 nm and the optimal growth temperature of InGaAs quantum dots was found to be between 480 and 465 . The success of high quality quantum dots fabrication and the study of the optimal growth condition are very helpful for the device applications of quantum dots. The result has been published in Japanese Journal of Applied Physics[9].

We have also used magneto-optics in high magnetic fields to investigate the InGaAs/GaAs QWs and QDs grown on (111)B GaAs substrate at different growing temperature. The structures show a large diamagnetic shift of the energy levels, and measurements of the anisotropy of the shift allow us to conclude that there is enhanced confinement in the dots. The ECWFs are also deduced from the diamagnetic shift. The in-plane ECWFs changed from 18.7 to 16.7 nm when the growing temperature varied from 525 to 450 °C. These measurements support that high quality quantum dots are formed and help us to understand the physics of quantum dots. The results are also publlished or submitted[10,11].

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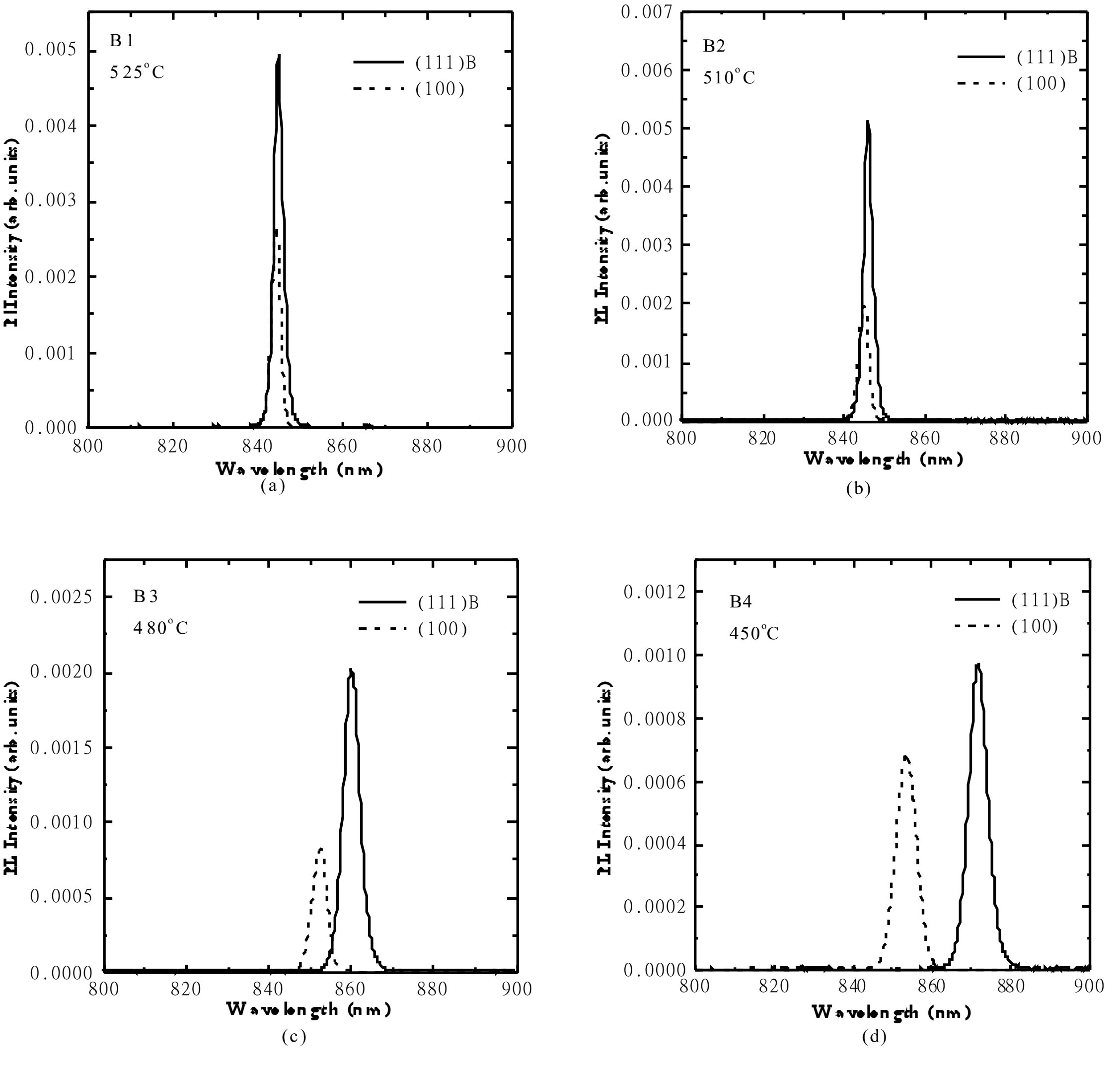
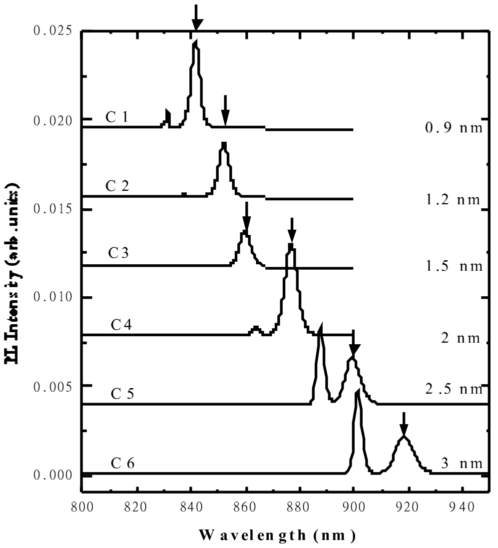


(a) (b) (c) (d)

Fig. 1 $In_{0.25}Ga_{0.75}As/GaAs$ QWs(all (100) samples and (111)B samples in (a),(b)) and QDs((111)B samples in (c), (d))



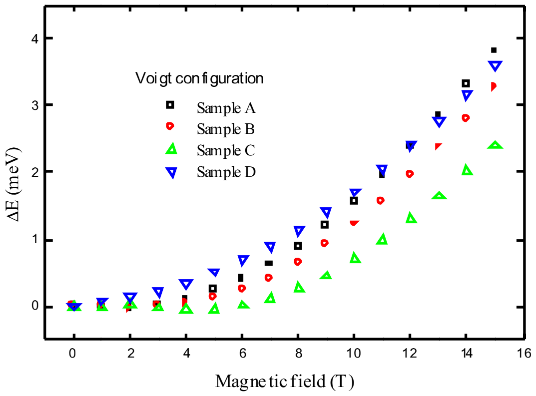


Fig.2 QWs and QDs(pointed by arrows) of various thickness.

Fig.3: The diamagnetic shifts of the PL lines, ΔE, for (111)B samples in Fig.1.