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# Fabrication of self-organized GaInNAs quantum dots on GaAs (311)B by atomic hydrogen-assisted RF-molecular beam epitaxy

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**Abstract.** We investigate the growth of self-organized GaInNAs quantum dots (QDs) on GaAs (311)B substrate by atomic H-assisted RF-MBE. The growth of GaInNAs QDs on GaAs(311)B is strongly dependent on the $N_2$ flow rate and RF power conditions. An ordered GaInNAs QDs array structure was successfully obtained by using a low RF power condition of 200W.

## 1. Introduction

Recently, low-dimensional self-organized semiconductor quantum dot (QD) structures have attracted intense research for applications to long wavelength lasers [1], which are required in 1.3 and 1.55μm optical fiber communication systems. However, due to the quantum size effect and highly compressive strain, it has been somewhat difficult to achieve long wavelength emission in self-assembled In(Ga)As QDs/GaAs system. Only recently, 1.3 and 1.55μm photoluminescence (PL) emission have been demonstrated using self-assembled In(Ga)As QDs embedded in strain reducing layers (SRLs) [2,3].

On the other, GaInNAs/GaAs systems has been a popular research candidate in order to develop long wavelength lasers, which has a strongly sublinear bandgap energy dependence between GaAs and GaN with a much larger alloy bandgap bowing parameter than for any other ternary semiconductors. Moreover, addition of nitrogen mainly increases the conduction band offset, which in turn improves the high temperature performance of semiconductor lasers [4]. Several groups have reported the growth of GaInNAs QDs by different epitaxial methods and demonstrated PL emission at 1.3 ~ 1.5μm range [5-7].

In this work, self-organized GaInNAs QDs were fabricated on GaAs (311)B substrate by atomic H-assisted RF-MBE in order to improve the size uniformity of QDs [8]. Previously, we have fabricated GaInNAs QDs on GaAs (001). Though room temperature PL emission at around 1.3μm was obtained, increasing QD size fluctuation was observed with increasing $N_2$ flow rate [9]. Here, we show that formation of structurally ordered GaInNAs QDs arrays is possible at low RF-power conditions.

## 2. Experimental

Self-organized $Ga_{0.6}In_{0.4}N_yAs_{1-y}$ QD structures were grown on GaAs (311)B substrates by atomic H-assisted RF-MBE. Each GaAs substrate was first subjected to surface cleaning at 580°C for 30 min with atomic H irradiation to obtain an atomically flat surface. Then a 300nm-thick GaAs buffer layer was grown at 580°C. After the growth of buffer layer, GaInNAs QDs of 7.7 ML thickness was grown at 480 or 500°C. For PL measurements, a 40nm-thick GaAs cap layer was further grown over the QDs layer. No post-growth annealing was performed. The $N_2$ flow rate and RF power were varied from 2.5 to 3.5 sccm and from 200W to 300W during the growth of GaInNAs QDs, respectively. The growth rate was kept at 1μm/h for all layers except for the QDs layer, for which the growth rate was reduced to 0.1μm/h. The N composition in GaInNAs QDs layer was determined by fitting the results of X-ray diffraction (XRD) obtained from separately prepared GaNAs samples grown on GaAs (001). We estimate as 2% for N composition in this work. The $As_4$ and $H_2$ back pressures during the growth were $1.0\times10^{-6}$, $4.5\times10^{-6}$ Torr, respectively. The growth process and surface morphology were studied *in situ* by reflection high-energy electron diffraction (RHEED), and *ex situ* by atomic force microscope (AFM). The optical characteristics were studied by photoluminescence (PL), and a 532nm semiconductor laser-pumped green laser was used as an optical excitation source.

## 3. Results and discussion

Figure1 show the AFM images of $Ga_{0.6}In_{0.4}N_{0.02}As_{0.98}$ self-organized QDs on GaAs (311)B fabricated with varying $N_2$ flow rate conditions, (a) 0sccm (InGaAs QDs), (b) 2.5 sccm, (c) 3.0 sccm, and (d) 3.5 sccm, respectively. The RF power and growth temperature were fixed to 300W and 500°C, respectively, which are identical growth conditions as for growth on (001) substrate in our previous work [8]. While a well ordered InGaAs QDs array with a small size fluctuation was formed on GaAs (311)B as in Fig.1 (a), larger size fluctuations and disordered QDs were formed with increasing $N_2$ flow rate as shown in Fig.1 (b), (c), and (d). The lattice mismatch relative to GaAs of both $Ga_{0.6}In_{0.4}N_{0.02}As_{0.98}$ and $In_{0.4}Ga_{0.6}As$ was almost the same and ~2.9%. Therefore, these differences on QDs formation likely to be caused by incorporating N atoms, which could become the central nucleation sites of QDs formation resulting in disordered QD structures with large size fluctuations in GaInNAs/GaAs system.

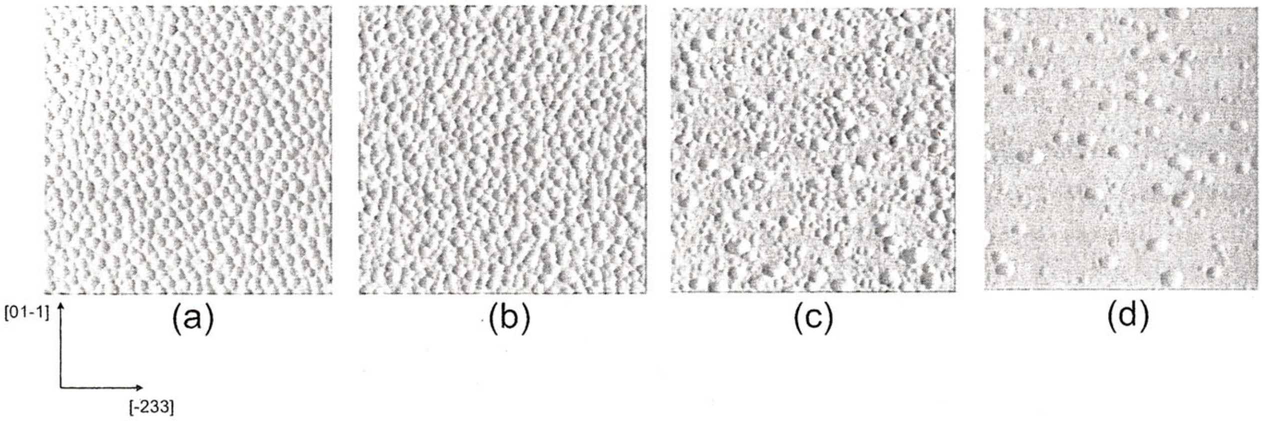

**Fig. 1** AFM images of $Ga_{0.6}In_{0.4}N_{0.02}As_{0.98}$ self-organized QDs on GaAs (311)B fabricated with varying $N_2$ flow rate conditions, (a) 0sccm (InGaAs QDs), (b) 2.5 sccm, (c) 3.0 sccm, and (d) 3.5 sccm, respectively. Scan size is 1μm×1μm.

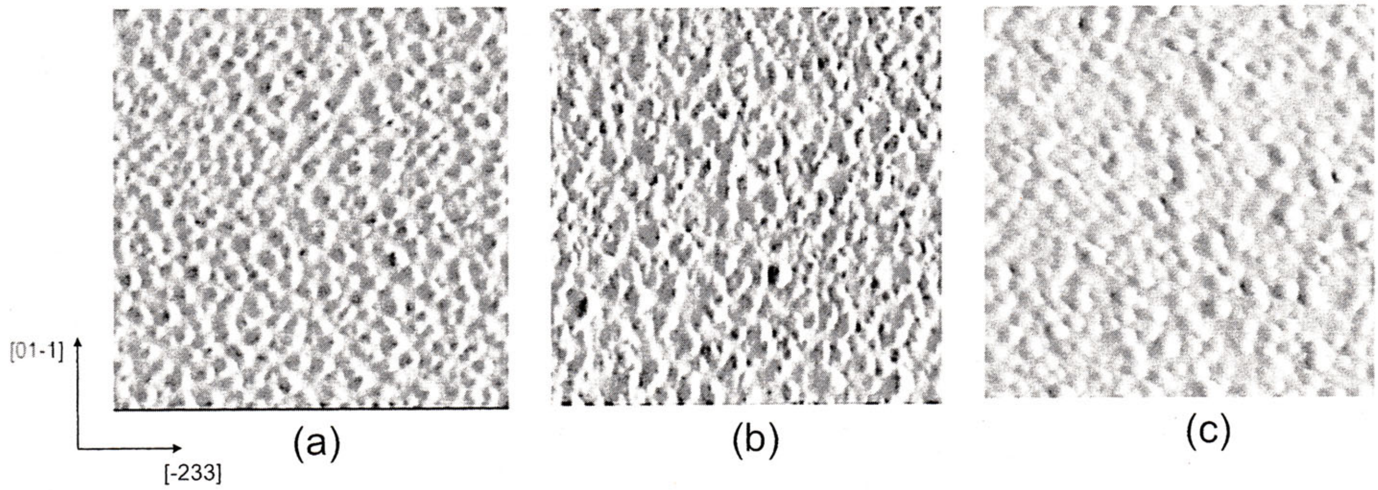

**Fig.2** AFM images of self-organized GaInNAs QDs on GaAs (311)B fabricated with varying RF power conditions; (a) 200W, (b) 250W, and (c) 300W, respectively. Scan size is 500nm × 500nm.

Figure2 show the AFM images of $Ga_{0.6}In_{0.4}N_{0.02}As_{0.98}$ self-organized QDs on GaAs (311)B substrates fabricated with varying RF power conditions, (a) 200W, (b) 250W, and (c) 300W, respectively. The $N_2$ flow rate and substrate temperature were set to 1.5sccm and 480°C in order to suppress the surface diffusion of N atoms. Clearly, we can see that the RF power significantly affects the growth of GaInNAs QDs. By lowering the RF power, the QDs size becomes smaller and size uniformity is improved. The average QDs diameter, height and density in Fig.2 (a) are 22.53nm, 3.9nm, and $1.26\times10^{11}$ $cm^{-2}$, respectively. The size fluctuation of GaInNAs QDs on GaAs (311)B of ~19% is smaller than that on GaAs (001) of ~24% [9]. We believe these results are caused by the localized strain field formed around N atoms, which then become the central nucleation sites of QDs formation. These nucleation sites are formed more easily under higher RF power conditions, while GaInNAs QDs array structures is more easily obtainable for lower RF powers.

Finally, Fig.3 shows the PL spectra measured at 10K for (a) InGaAs QDs, (b) GaInNAs QDs on GaAs (311)B, and (c) GaInNAs QDs on GaAs(001), respectively. The excitation power was ~1 $W/cm^2$. The PL peak shifts from 956nm for InGaAs QDs to a longer wavelength for 1024nm of GaInNAs QDs on GaAs (311)B as in Fig.3 (b), and 1049nm for GaInNAs QDs on GaAs (001) as in Fig.3 (c). It appears that the average N composition of GaInNAs QDs on GaAs (311)B is smaller than that on GaAs (001) from PL results. Further, PL intensity of GaInNAs QDs on GaAs (311)B is weak and emission from localized states around 900nm is observed. Moreover, FWHM of PL peaks of both GaInNAs QDs are much broader than that of InGaAs QDs due to increasing size inhomogeneity. Consequently, the optical properties of QDs on GaAs (311)B still need much improvements, although the uniformity of QD size have been improved and ordering of QDs array is obtainable.

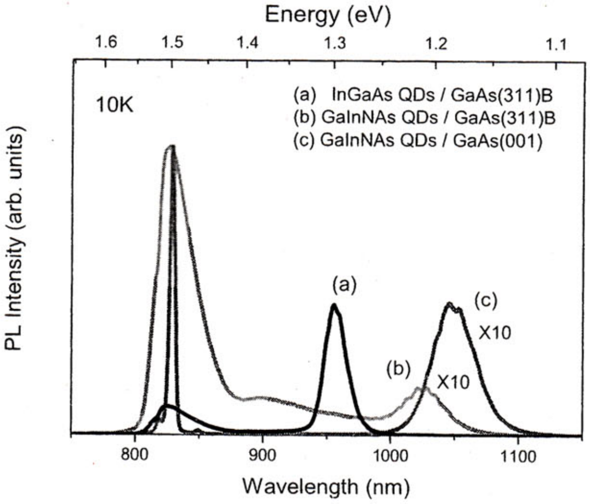

**Fig.3** PL spectra at 10K of as-grown, non-annealed (a) $In_{0.4}Ga_{0.6}As$ QDs on GaAs (311)B and (b) $Ga_{0.6}In_{0.4}N_{0.02}As_{0.98}$ QDs on GaAs (311)B and (c) grown on GaAs (001), respectively.

## 4. Summary

We have fabricated GaInNAs QDs on GaAs (311)B substrates by atomic-H assisted RF-MBE. The growth of GaInNAs QDs on GaAs(311)B is strongly dependent on the RF power conditions, and an ordered GaInNAs QDs array structure was successfully obtained by using a low RF power condition of 200W. Lower RF powers result in less damage to QDs properties. Although uniformity of QD size can be improved and ordering of QDs array is obtainable, the optical properties still need much improvements by optimizing the growth conditions.

## 5. Acknowledgements

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