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NANOTEMPLATE-ENABLED ARRAYS OF HIGHLY HETROENEOUS NANOSTRUCTURES FOR INFRARED DE

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Final Report

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14. ABSTRACT

This Final Technical Report summarizes the salient accomplishments under this grant which, though awarded for the period April 1, 2010 to Mar 31, 2015, fell victim to the federal government mandated Sequestration order that went into effect on March 28, 2013 and thus no funds were made available after March 31, 2013. The report thus can only provide status essentially as of summer 2013 as very little could be done without funds to provide for laboratory materials and supplies. In spite of such setback, the following significant goal was reached: highly lattice mismatched (~3.5%) GaAs/In0.5G0.5aAs single quantum dot on <30nm GaAs mesa tops were realized with spectral emission uniformity an order of magnitude better than the typical lattice-mismatch strain-driven 3D island quantum dots that have provided randomly obtained single quantum dots for single photon emission experiments. This makes the nanotemplate-directed QD arrays well suited as the single photon emitter arrays much sought for quantum cryptography and information processing applications. Regretably, the sudden discontinuation of the grant did not allow exploration of this potential.

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Final Technical Report

Grant No. AFOSR FA9550-10-1-0066

Nanotemplate-Enabled Arrays of Highly Heterogeneous Nanostructures for Infrared Detection and Power Generation

Period: April 1, 2010 to March 31, 2014

Program Manager: Dr. Kitt Reinhardt (AFOSR) April 1, 2010 to Aug.30, 2012
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Abstract

This Final Technical Report summarizes the salient accomplishments under this grant which, though awarded for the period April 1, 2010 to Mar 31, 2015, fell victim to the federal government mandated Sequestration order that went into effect on March 28, 2013 and thus no funds were made available after March 31, 2013. In spite of such a setback, the following significant goal was reached: highly lattice mismatched (~3.5%) GaAs/$In_{0.5}Ga_{0.5}As$ flat-top quantum dot on <30nm mesa tops were realized with spectral emission uniformity an order of magnitude better than the typical lattice-mismatch strain-driven 3D island quantum dots dubbed self-assembled QDs. This makes the nanotemplate-directed QD arrays well suited as single photon emitter arrays much sought for quantum cryptography and information processing. Regrettably, the sudden discontinuation of the grant did not allow pursuing exploration of this potential.

I. Objectives:

The overall objectives of this program were to examine the fundamental aspects of the accommodation of the difference between lattice constant, chemical bonding, and crystal structure of an overlayer deposited epitaxially on structurally patterned substrate as a function of the patterned mesa lateral size, depth, and shape. The aim is realizing, via purely growth control, spatially ordered arrays of defect-free and spectrally uniform high optical quality semiconductor quantum nanostructures made of highly dissimilar materials as required by systems for advanced applications in the infrared and optical regimes. The approach to synthesizing, *in-situ*, nanostructure arrays via patterned *nanotemplate-directed size-reducing epitaxy* that underpins this program was pioneered by the PI and an illustrative example for the case of lattice matched combination GaAs/AlGaAs is shown in Fig.1.

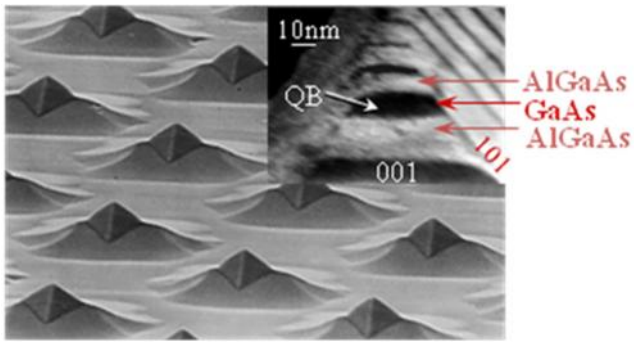

Fig.1 Shows a SEM image of pyramidal structures synthesized via engineered surface stress-directed size-reducing growth on an array of square nanoscale mesas on GaAs(001) substrate. Inset shows a TEM image of the apex region of the pyramid comprising GaAs (dark) /AlGaAs (light) based quantum dots. [From K. C. Rajkumar et al. Jour.Vac. Sc.Tech. **B12**, 1071 (1994)]

To explore the expected benefits of this approach to integrating highly dissimilar semiconductor materials, the research program was organized into the following synergistic aims and parallel tasks:

Specific Aims Planned & Pursued:

1. Develop methodologies and protocols for fabricating nanotemplate arrays with lateral sizes <50nm and depths between 50nm and 500nm.

2. *In-situ* atomic-scale examination of the evolution of growth of highly inhomogeneous overlayers on such nanotemplates using a custom-designed UHV STM system.

3. Develop methodologies and protocols for synthesizing 3-dimensionally confined quantum nanostructures (quantum dots) via atomic-layer control on growth of buffer layers and of highly lattice-mismatched overlayers on the nanotemplate mesas utilizing molecular beam epitaxy.

4. Characterize such grown quantum dots (QDs) structurally via HRTEM.

5. Characterize these nanotemplate QD arrays optically via broad area and micro-photoluminescence (μPL) with a focus on spectral response uniformity.

6. Developing appropriate instrumentation for and examining the single photon emission characteristics of such nanotemplate-based on-site single QDs accessible in a regular array.

The material system chosen as a vehicle for exploring these ideas and approaches was the InGaAs/AlGaAs combination that provides up to 7% lattice mismatch (for InAs/GaAs) on GaAs

substrates and 11% on Si substrates (InAs/Si) for which the chemical bonding inhomogeneity involves the challenge of integrating heteropolar-homopolar material combination.

II. Summary of Major Accomplishments

(1) Nanotemplate Array Fabrication

We fabricated, for the first-time, pristine high-aspect ratio (6:1) GaAs nanotemplate arrays comprising *as-etched* nanopillars having (100) top and nearly vertical {100} side walls. On such nanopillars was carried out molecular beam epitaxial growth of (a) the lattice-matched GaAs/AlGaAs quantum structures and (b) the highly heterogeneous GaAs/InGaAs system with lattice mismatch up to 7% for GaAs/InAs to realize single quantum dots with flat top morphology on the *in-situ* size-reduced nanopillar tops having lateral sizes in the range of 10nm to 50nm. The covered range of deposited composition and thickness provided nanotemplate quantum dots that emit between 900nm and1200nm, covering the near infrared regime of interest. (Details in Sec.III)

(2) Transmission electron microscopy utilizing both chemical and phase contrast for, respectively, imaging layer contrast (such as GaAs against AlGaAs or InGaAs) and resolving lattice planes was used to characterize the grown nanotemplate-directed quantum nanostructures including quantum dots. These studies were carried out using our unique approach to cross-sectional TEM imaging of nanotemplate-based nanostructures that does not require TEM specimen thinning.

The samples were first examined at the TEM facility at USC and then those worthy of being examined with a microscope with nearly-atomic level resolution, such as at AFRL WPAFB, were sent to WPAFB for collaborative investigations with Dr. K. Mahalingam and Dr. Gail Brown. Such studies were underway when the Sequestration triggered cut forced them to be stopped.

(3) Micro Photoluminescence (μPL) studies of nanotemplate quantum dot (NTQD) spectral response and uniformity of the array:

As the nanotemplate-directed single or multiply stacked quantum nanostructures created via growth on spatially regular arrays of nanotemplates can offer significant improvement in spectral emission uniformity over the common place implementations based upon spatially randomly located lattice mismatch strain-driven 3D island self-assembled quantum dots (SAQDs) that exhibit large composition, size, and shape variation as manifest in their spectral emission nonuniformity (PL linewidths >50meV of the SAQD ensemble are common place), establishing an appropriate μ-PL measurement system to measure PL from individual NTQDs and thus assess the realized advantage in reducing spectral nonuniformity took high priority. Having established such an experimental station early in the program, measurements of statistically significant number of nanotemplate quantum dots established that we achieved control of QD spatial position to ~10nm (versus >100nm for SAQDs) and the PL peak position variation ~2-4meV (versus typically >50meV for SAQDs), an order of magnitude improvement. The low (liquid Helium) temperature μ-PL measurements revealed NTQD emission lines with linewidths of ~300 μeV limited by the instrumental resolution. (Details in Sec. III)

(4) Exciton Decay Dynamics:

To examine the dynamics of exciton decay in single nanotemplate quantum dots we set up and tested the necessary low-temperature time-resolved micro-photoluminescence (TR-μPL) system capable of characterizing the emission from single nanotemplate quantum dots down to liquid helium temperature. This served as the precursor for setting up the instrumentation for examining the photon emission statistics to ascertain the potential of single NTQDs as single photon emitters with highly improved spectral characteristics so critically needed for quantum information processing studies.

(5) Single Photon Emission Characteristics:

In Fall 2012 we extended the TRPL system to the Hanbury-Brown and Twiss setup for measurement of single photon emission statistics. In Spring 2013 we were in the midst of further refinements in the optical system to acquire in reasonable time the signal-to-noise ratio needed to measure, for the first time, single photon emission characteristics from a nanotemplate-based *flat-top* single quantum dot when, most regrettably, the Sequestration cut hit and the lack of funds prevented any further work.

(6) Atomic-Scale Structure Evolution

An important element of understanding and controlling the growth of quantum nanostructures comprising highly heterogeneous material combinations is the examination of structural evolution and accompanying electronic state information for nanomesas (both top and sidewall) as a function of sub-monolayer incremental depositions of the chosen overlayer. Towards this goal we undertook and finalized the design, got made, and tested a UHV STM system with the unique feature of *tip re-positioning after sample dismounting/remounting to an accuracy of less than a micron*. The testing revealed that the system satisfied the designed dismounting/remounting tip repositioning accuracy as illustrated in Fig.2 below by the black arrow in the images of a mica sample taken with demounting and remounting the sample.

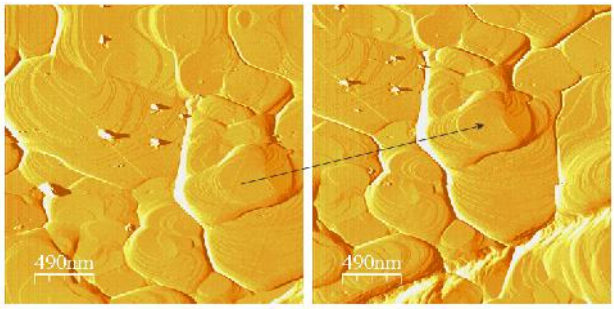

Fig.2 Shows STM images of the same area of a mica sample with sample demounting and remounting between the left and right images. The arrow marks the tip return to the same position with an accuracy better than one micron.

The atomic resolution however was limited to restrictive conditions indicating the need for the vendor to make further design adjustments. This was underway when the Sequestration cut hit, preventing any further work on developing this unique instrument.

III. Some Details of the Growth and Optical Behavior of Nanotemplate Single QDs:

III.1 Fabrication of Nanotemplate Arrays:

The *in-situ* realization of a designed array of nanomesas with surface linear dimensions <50nm on which quantum dots, single or vertically stacked, are subsequently synthesized via purely growth control, is a two-step process: first is the fabrication of the *as-patterned and*

etched arrays of GaAs nanomesas of surface linear dimensions 50nm to 500nm and varying sidewall angles using electron beam lithography and chemical etching; second is the size-reducing growth of GaAs buffer layer to overcome residual contamination and defects induced by the etching process while reducing the nanomesa size to the desired range of <50nm for the subsequent synthesis of the quantum dots of highly heterogeneous materials.

The *as-patterned* mesa array area on the substrate was designed to contain mesas of sixteen different sizes in the patterned region for structural and optical studies and an L-shaped unpatterned region is used to allow in-situ growth condition monitoring and control using RHEED (reflection high energy electron diffraction) pattern and intensity dynamics to monitor the surface and growth front conditions. All nanomesas in the patterned region are created with their four edges along the [100] direction to enable symmetric adatom migration from the four side walls to the mesa top. Nanomesas of size 50nm to 500nm with near-vertical sidewall angles are created by wet chemical etching using 4:1:20 $NH_4OH:H_2O_2:H_2O$ after patterning. Figure 3(a) shows an SEM image of an as-etched mesa array with 5μm pitch and size 324nm and Fig. 3(b) shows a 45˚ tilted SEM image of an individual mesa in that array.

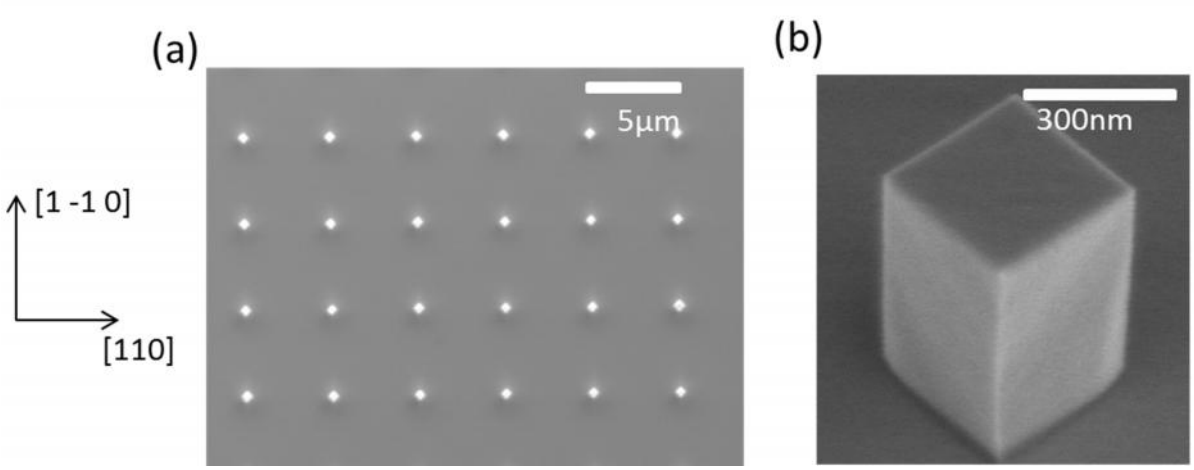

Fig.3. (a) Top view SEM image of mesa array with 5μm pitch and of size 324nm. (b) 45˚ tilted view SEM image of one mesa out of the array. Nanomesas have near vertical side wall after wet chemical etching.

Such as-etched substrates were mounted on Mo blocks and degassed in the modutrac of the Riber 3200 MBE system and then transferred to the growth chamber for thermal deoxidation. Subsequently a GaAs buffer layer with a few monolayer (ML) thick AlGaAs marker layers (for post-growth TEM examination) interspersed periodically was grown at T=600˚C, P_{As}=2.5E-6 Torr, and Ga delivery time of τ_{Ga}=4sec/ML (growth rate of 0.25ML/sec) to (1) recover from any residual damage remaining after deoxidation and (2) control the mesa top size reduction to bring it to the desired size < 30nm for the growth of single flat-top NTQD on the mesa top.

III.2 Growth of Nanotemplate Quantum Dots (NTQDs)

The InGaAs flat morphology NTQDs were grown at τ_{In}=4sec/ML and at temperature depending on the In composition (T=520˚C for $In_{0.5}Ga_{0.5}As$ QD, T=480˚C for InAs QD, the two types of samples used for optical studies). The InGaAs QDs were capped by 200ML GaAs to

create three dimensional confinement and to protect the QDs from impurities and defects on the GaAs surface.

We note that there are two stages of mesa top pinch-off with increasing deposition amount for (001) top face nanomeasas with edges along [100] as we demonstrated earlier [see A. Konkar et al., Jour. Cryst. Growth **150**, 311 (1995)]. In the first stage {103} type planes dominate mesa top size reduction and lead to the first mesa pinch off by {103} planes. Subsequent deposition and atom migration leads to the change from {103} planes to {101} planes while opening up a new top (001) surface. This newly opened mesa top size first grows bigger then reduces till it reaches the second mesa pinch off controlled by the {101} planes. Figure 4 shows SEM images of mesas at various stages: (a) {103} plane dominated (001) mesa top surface reduction; (b) the first mesa pinch off by {103} planes; (c) {101} plane dominated newly opened (001) mesa top surface reduction. Thus, using this growth mechanism, two types of flat QDs can be grown: (1) QD bounded by {103} planes and (2) QD bounded by {101} planes as shown in Fig.5 (d) marked in red.

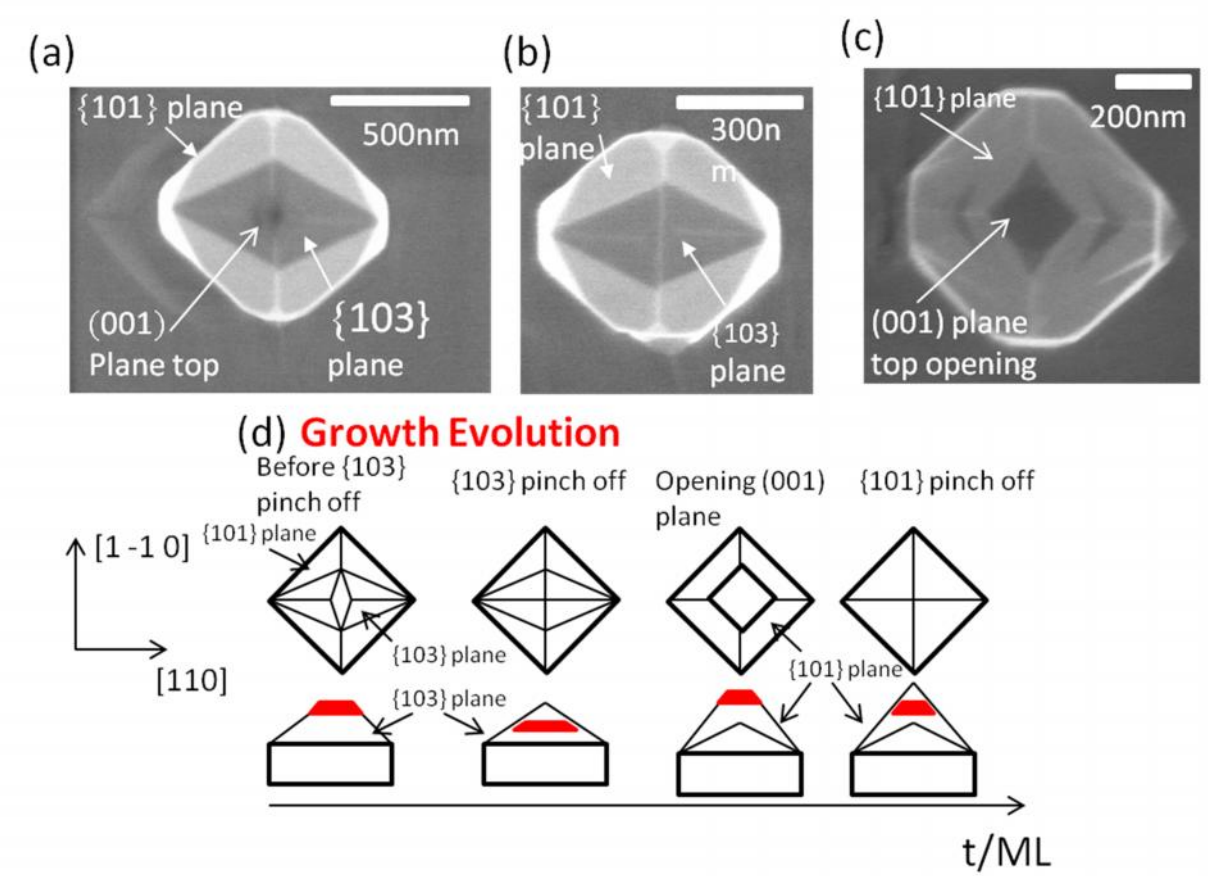

Fig.4 Growth Evolution on Nanomesas. (a) top view SEM image of mesa with (001) mesa top surface bounded by {103} plane (b) top view SEM image of mesa at the first stage of mesa pinch-off bounded by {103} plane and (c) top view SEM image of mesa with newly opened (001) mesa top surface bounded by {101} plane after the first mesa pinch off by{103} plane.(d) schematic drawing of the growth evolution and geometry of two kinds of QD obtainable from nanotemplate-directed growth.

Illustrative optical results on two classes of samples, one with 12ML flat InAs QD on mesa top bounded by {101} planes and the other with 4.25ML flat $In_{0.5}Ga_{0.5}As$ QD on mesa top bounded by {103} planes having emission at different wavelengths are discussed next .

III.3 Optical Properties of Nanotemple-Directed Flat Top QDs

To carry out optical measurements on individual nanotemplate quantum dots, a home-built micro-PL setup was established and tested. A 40× NA 0.65 objective lens is used to focus excitation light down to 2 μm diameter to study the optical response of individual mesas in samples mounted in a LHe cooled cryostat. A Ti:S laser in the cw mode tuned to 780nm was used for excitation for time integrated PL studies. The same system in a 76MHz fs pulsed mode was used in time resolved PL (TRPL) studies of the exciton decay behavior. Signal collection was through the same objective lens as used for focusing light and excitation. The PL from the sample was filtered from the excitation beam by a long pass filter and collected by a multimode optical fiber patch cord directed to a 300mm focal length spectrometer with an exit port connected to an InGaAs array detector for time integrated PL measurements. The spectral resolution of the setup is ~300μeV using the combination of a 1200 g/mm grating and ~100 μm entrance slit width that enables reasonable signal level. The instrument response function (IRF) of the time resolved measurement has a width of ~ 700ps, limited by the time jitter of the APDs.

Time integrated PL spectra at 77.4K and 8K were collected from the two samples, one with 12ML flat InAs QD on mesa top bounded by {101} planes and the other with 4.25ML flat $In_{0.5}Ga_{0.5}As$ QD on mesa top bounded by {103} planes as noted in Sec.II. The PL spectra at these two temperatures from the 12ML flat InAs QD with a base length of ~15nm and height ~5nm as estimated from growth evolution are shown in Fig.5. At 77K emission at 1122.5nm with a linewidth of 4.9meV is seen. Power dependent studies show that the PL intensity saturates at very low power of 4μW (~ 130 W/cm^2) indicating the 3-dimensionally confined nature of the electron states involved. The QD PL linewidth is broadened by thermal energy, K_BT ~ 6.6meV, i.e. phonons which prevents revealing the true linewidth and hence the radiative-decay limited coherence lifetime of QD. Significantly reducing thermal energy to K_BT ~ 700 μeV by cooling the specimen down to 8K, two emission lines with linewidths of 320μeV separated by 660 μeV are revealed. The two lines can be expected as arising from e-h transitions involving hole p_x or p_y type Bloch states owing to some growth asymmetry, the present QDs acquire a rectangular base thus breaking the degeneracy of p_x and p_y hole states in a QD with square base. At 8K the thermal energy is comparable to the energy difference between p_x and p_y hole state transitions and thus with fewer phonons both peaks are revealed.

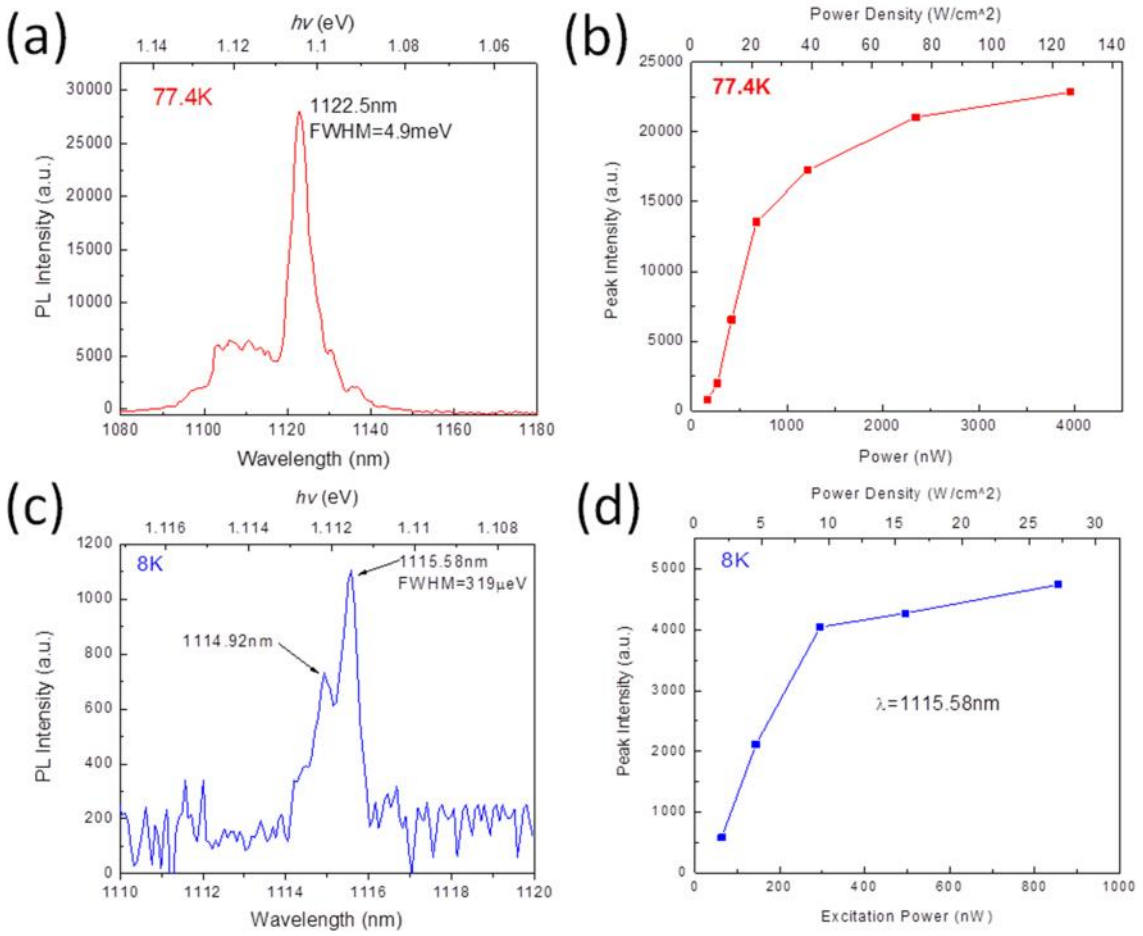

Fig.5 PL spectra from 12ML InAs QD bounded by {101} planes at 77.4 K and 8.0 K. (a) PL spectrum collected at 77.4K and excitation power of 675 nW (~21 W/cm^2). (b) Power dependence of PL peak intensity at 77.4K. (c) PL spectrum collected at 8.0 K and excitation power of 400 nW (~13 W/cm^2) (d) Power dependence of PL peak intensity at 8.0 K. For all cases, the excitation is with cw Ti:S laser tuned to 780 nm.

The PL spectra of the 4.25ML flat $In_{0.5}Ga_{0.5}As$ QD on mesa tops bounded by {103} planes and with a base length of ~21nm and height of ~3nm as estimated from growth evolution are shown in Fig.6. The PL emission is near the expected wavelength of 930.5nm with a linewidth of 6.3meV at 77.4K. The PL intensity saturates at a very low power of 3.5μW (~100 W/cm^2) on the mesa which reveals the 3-dimensionally confined nature of the participating electronic energy states. Unlike the binary InAs QD of the preceding case, the linewidth in this case of an alloy QD is broadened not only by thermal energy of phonon motion in the QD but also by the alloy disorder within the QD. Lowering the temperature to 8K, a single primary peak with a linewidth of 340 μeV is seen as shown in Fig.6(c). The absence of two clear peaks from p_x and p_y hole states in the alloy QD is probably because of the mixing of p_x and p_y hole states due to alloy disorder as well as the diamond like base for {103} plane bounding the QD. The coherence lifetime of QD, which is commonly taken to be inversely related to the measured PL emission linewidth, is found to be ~1ps for both kinds of QDs. The linewidth observed at 8K for either the

binary InAs QDs or alloy $In_{0.5}Ga_{0.5}As$ QDs does not reveal the true linewidth but is measurement resolution limited. Therefore, the ~1 ps coherence lifetime derived from the integrated PL data is a lower bound.

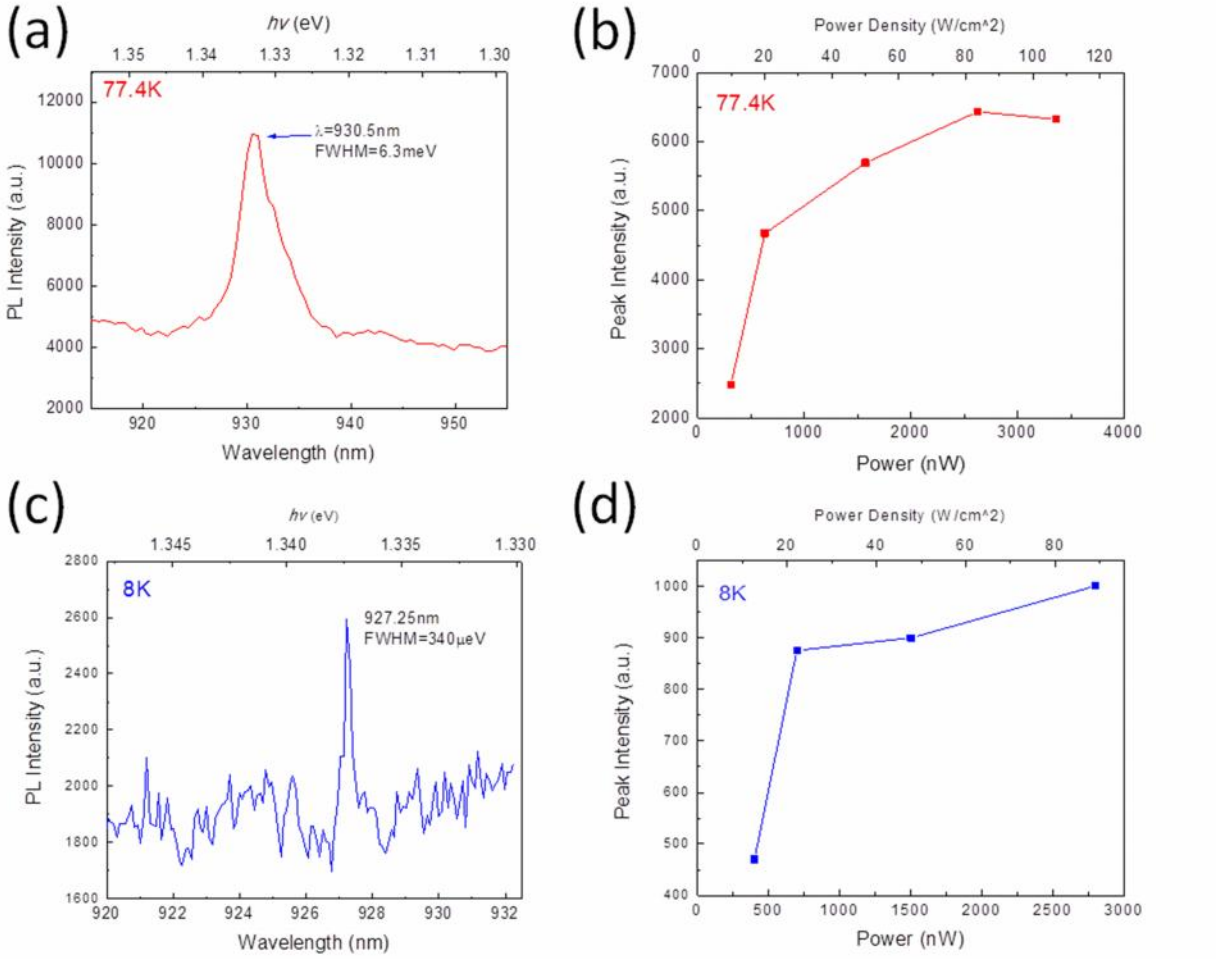

Fig.6 PL spectra from 4.25ML $In_{0.5}Ga_{0.5}As$ QD bounded by {103} planes at 77.4K and 8.0 K. (a) PL spectrum collected at 77.4K and excitation power density of 1000 nW (~32 W/cm^2). (b) Power dependence of PL peak intensity at 77.4K. (c) PL spectrum collected at 8.0 and and excitation power density of 200 nW (~6.4 W/cm^2) (d) Power dependence of PL.

In Fig.7 we show the time-resolved PL dynamics of the 4.25ML flat $In_{0.5}Ga_{0.5}As$ QD with emission at ~930nm thus making it compatible with our Si APD based detection system. A radiative decay time of ~1ns is measured. Considering the instrument's own response function, the deconvoluted radiative decay time is ~0.8ns, consistent with decay time of single SAQD[5,17]. Lastly, to assess the uniformity of emission from this class of *flat* InGaAs/GaAs *single* QD located on top of nanomesas in regular arrays, three mesas with 15μm separation between them for each of the two categories were examined. The 12ML flat InAs QD on mesa tops bounded by {101} planes in the array show PL emission at 1122.5±1.2nm with a linewidth of 5.6±1meV at 77.4K while the 4.25ML flat $In_{0.5}Ga_{0.5}As$ QD on mesa tops bounded by {103} planes show PL emission at 930.5±3.8nm with a linewidth of 6.3±1meV at 77.4K. The uniformity of this new class of QD is higher than that of SAQDs.

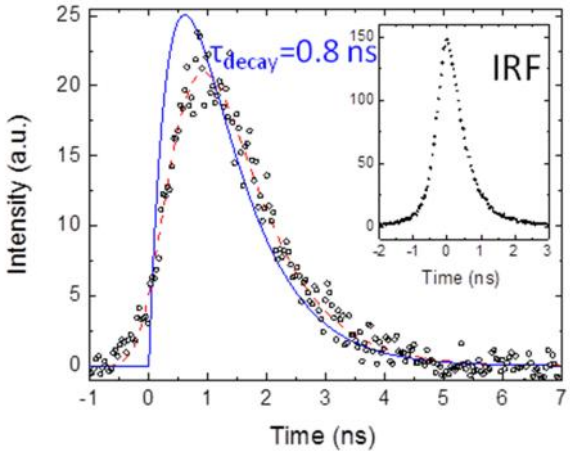

Fig.7 TRPL data for a 4.25ML $In_{0.5}Ga_{0.5}As$ QD bounded by {103} planes at 8.0 K with detection wavelength at 927.25nm and 76MHz fs pulsed Ti:S laser tuned to 780nm as excitation source. The measured TRPL data are plotted as circles with their reconvoluted fitting (red dash line) and the deconvoluted fitting (blue solid line) obtained by considering the instrument response function (IRF) shown in the insert. The decay time of the QD PL emission is 0.8ns after deconvolution.

To summarize, the growth and optical response of *flat top* InGaAs single QDs located on the top of GaAs(001) nanomesas in an array was examined. The size and shape of the single QD on the nanomesa is controlled using the engineered surface-stress gradient directed adatom interfacet migration during growth. Knowing the geometry of planes present on the as-designed nanomesas and controlling the inter-facet migration lengths of atoms by controlling the arsenic pressure, cation flux, and substrate temperature, we control the evolution of nanomesas during growth and deposit InGaAs at the appropriate stage to form strain released truncated-pyramidal shape GaAs/InGaAs/GaAs QDs with base lengths of <30nm on mesa tops bounded by {103} or {101} planes. This class of QDs overcomes the two basic limitations of the much used island SAQDs: (i) the structural and chemical inhomogeneity and (ii) random positioning. In addition, optical results reported here on this new class of QDs indicate that their exciton coherence time is longer than ~1ps and the radiative decay time is ~0.8ns, comparable to SAQDs, but with higher uniformity than SAQDs. These features taken together make the flat-morphology quantum box like QDs good candidates for single photon source array applications.

Single Nanotemplate Quantum Dot Photon Emission Statistics

To study and measure single photon emission characteristics of NTQDs, in Fall 2013 we extended our micro-PL setup to include the capability of measuring the second order time correlation function (the $g^{(2)}$ function) for photons emitted by the NTQDs. The emitted light from the NTQD is collected through the microscope, filtered by spectrometer and goes through a 50/50 beam splitter with two Si APDs on each side to realize the classic Hanbury-Brown and Twiss setup for $g^{(2)}$ measurement. Picosecond discriminators, delay unit, and time-to-pulse height converter are used for processing the electronic signal from the APDs to finally display the

measured correlation function. The timing resolution of the electronics is ~10ps, tested using a signal with known shape from the function generator and the instrument response function (IRF) linewidth of the $g^{(2)}$ setup tested using the 76MHz Ti-Sa laser line at 875nm is 1.5ns, mainly limited by the time jitter of the APDs

Considerable effort was put in to improve the signal-to-noise ratio of our $g^{(2)}$ setup. New APDs with reasonably low background counts (<200c/s) and large enough effective area (150μm) were purchased and installed to enhance the signal-to-noise ratio of the detectors. Adjustment of design of filters and splitters in the microscope was carried out to minimize possible loss in the microscope. NIR optimized lens pair were tested and used to eliminate aberration of collected light from NTQD to enhance the collection efficiency of setup. However, with no funds available for laboratory materials and supplies including cryogenic fluids the work had to be stopped.

Presentations:

- (Invited Talk) A. Madhukar, "Heteroepitaxy: Beyond Lattice Mismatch", MRS Spring Meeting, April 25-29, 2011 (San Francisco).
- (Plenary Talk) A. Madhukar, "Epitaxy: An atomistic and kinetic view for all length scales", SPIE Photonics, August 21-25, 2011 (San Diego).
- (Contributed talk) Jiefei Zhang, Zachary Lingley, Siyuan Lu, and Anupam Madhukar "Nanotemplate-Directed InGaAs/GaAs Quantum Dots: Towards Single Photon Emitter Arrays", North American MBE Conference, Banff, Canada, Oct 5-11, 2013.

Publications:

1. Jiefei Zhang, Zachary Lingley, Siyuan Lu, and Anupam Madhukar "Nanotemplate-Directed InGaAs/GaAs Quantum Dots: Towards Single Photon Emitter", Jour. Vac. Sc. Tech. B **32**, 02C106 (2014)

Personnel:

Graduate Students

1. Tetsuya Asano, (Materials Science) May 16, 2010- Dec.31, 2010
2. Christopher Berry, (Elect. Eng.) May 16, 2010- Aug, 15, 2012
3. Jiefei Zhang, (Physics) May16, 2012- Dec, 31, 2013
4. Zachary Lingley, (Materials Science) Aug.16, 2012- Dec. 31, 2013

Postdoc

1. Vivek Antad, Postdoctoral Fellow, Jan 2013-May 2013

1.

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FA9550-10-1-0066

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Anupam Madhukar

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. Kenneth Goretta

Reporting Period Start Date

04/01/2010

Reporting Period End Date

03/31/2014

Abstract

This Final Technical Report summarizes the salient accomplishments under this grant which, though awarded for the period April 1, 2010 to Mar 31, 2015, fell victim to the federal government mandated Sequestration order that went into effect on March 28, 2013 and thus no funds were made available after March 31, 2013. In spite of such a setback, the following significant goal was reached: highly lattice mismatched (~3.5%) GaAs/In0.5Ga0.5As flat-top quantum dot on <30nm mesa tops were realized with spectral emission uniformity an order of magnitude better than the typical lattice-mismatch strain-driven 3D island quantum dots dubbed self-assembled QDs. This makes the nanotemplate-directed QD arrays well suited as single photon emitter arrays much sought for quantum cryptography and information processing. Regrettably, the sudden discontinuation of the grant did not allow pursuing exploration of this potential.

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Jiefei Zhang, Zachary Lingley, Siyuan Lu, and Anupam Madhukar "Nanotemplate-Directed InGaAs/GaAs Quantum Dots: Towards Single Photon Emitter", Jour. Vac. Sc. Tech. B 32, 02C106 (2014)

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Sometime in September 2012, program manager changed from Dr. Kitt Re1nhardt to Dr. Dr. James Hwang.

Extensions granted or milestones slipped, if any:

Sequestration induced cut in all funding for the last two years (i.e. from April 01, 2013 to Mar. 31, 2015) of the originally approved program. On Nov 30, 2013 was given a No Cost Extension for the period April 01, 2013 to March 31, 2014.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

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Appendix Documents

2. Thank You

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