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QDIP Web Input

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1. Background:

Sensors have to meet stringent requirements for space applications such as high quantum efficiency, extremely low noise, high temperature (or uncooled) operation, radiation hardness, narrow line widths, high output power, etc. Semiconductor quantum dots are very promising for optoelectronic device applications because of their capabilities for carrier confinement in all 3-dimensions, creating discrete energy levels with a sharp delta-function-like density of states, large optical nonlinearity, normal incidence radiation absorption, lower dark current (which results from weak electron-phonon coupling), and high radiation tolerance. Although fabrication methods using self-organization, such as Stranski-Krastanov growth, are being widely studied, site and size control multi layer quantum dots material has not been achieved to date. On the other hand, Stranski-Krastanov self-assembled quantum dots could not produce focal plane array worthy materials yet. This motivated us to continue the materials and device structure improvement of self-assembled QDIPs, and development of site and size controlled semiconductor quantum dots by using molecular beam epitaxial (MBE) growth on GaAs substrates

2. Objectives:

The objectives of this task are following:

1. Develop and demonstrate the growth of multi layer site and size controlled III-V compound semiconductor quantum dots on standard GaAs substrates.
2. Develop low dark current and high responsivity self-assembled QDIP material at JPL.
3. Characterize QDIPs optically and electrically. Fabricate and demonstrate QDIP focal plane array.

3. Technical Approach:

As shown in Fig. 1, in a self-organizing approach, quantum dots with various sizes are randomly distributed on the surface. This randomness in size and nucleation sites makes these self-organized quantum dots less attractive for optoelectronic devices. If the formation of sites of self-organized quantum dots are arbitrarily and precisely controlled, then the density and size of the quantum dots can be manipulated independently, and as a result, we should be able to exploit the advantages that come with the 3-dimensional quantum confinement of carriers.

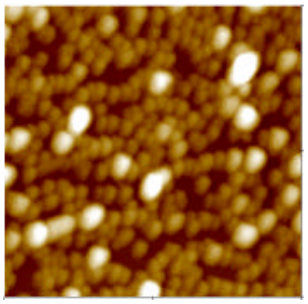

Figure 1. 2 mm x 2 mm AFM scan of typical self-assembled InAs Q-Dots on an InP substrate

Our approach to fabricate site- and size-controlled quantum dot devices starts with our recently installed JEOL JBX-9300FS electron beam lithography system shown in Fig. 2. This is the most

advanced E-beam system in the world, with only 4 other organizations (NEC, Lucent, Chalmers University, and Philips) owning the same tool. The specifications relevant to this project are the minimum spot diameter of 4 nm, the minimum spot-to-spot spacing of 1 nm, and the maximum acceleration voltage of 100 kV.

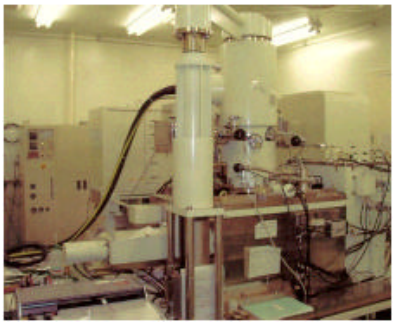

Figure 2. JPL electron beam lithography system (JEOL JBX-9300FS)

Our approach is to define large areas (active regions of many devices per wafer) of site and size-controlled quantum dots (see Fig. 3). To achieve this we will E-beam expose the active areas with arrays of minimum diameter E-beam spots separated by relatively large (non-overlapping) spot-to-spot spacing (e.g. 20 nm). The field-emission electron gun on our machine allows us to do this with reasonable currents (nA) so that a 3" wafer with 20% active area coverage could be exposed in several hours. Following exposure, the resist will be developed in one of two methods: high contrast or low contrast. In the first method (high-contrast), the exposed resist will be developed to form sharp-sidewall holes in the resist all the way to the substrate. Because the resist is a polymeric material, the holes will be larger than the 4 nm E-beam spot, perhaps as large as 15-20 nm, but this may be sufficient to control the quantum-dot growth. In the second method we develop the resist in a low-contrast (analog) manner to form dimples in the resist that mimic the beam profile as shown in Fig. 3. Using a transfer etch (Cl2 based dry etching) process that etches the substrate faster than the resist, it may be possible to transfer the very narrow portions of the resist dimples into the substrate. These dimples would then serve as nucleation sites for size-controlled quantum dot growth. The patterning flexibility of the E-beam would allow active areas of any shape to be filled with these quantum-dot arrays.

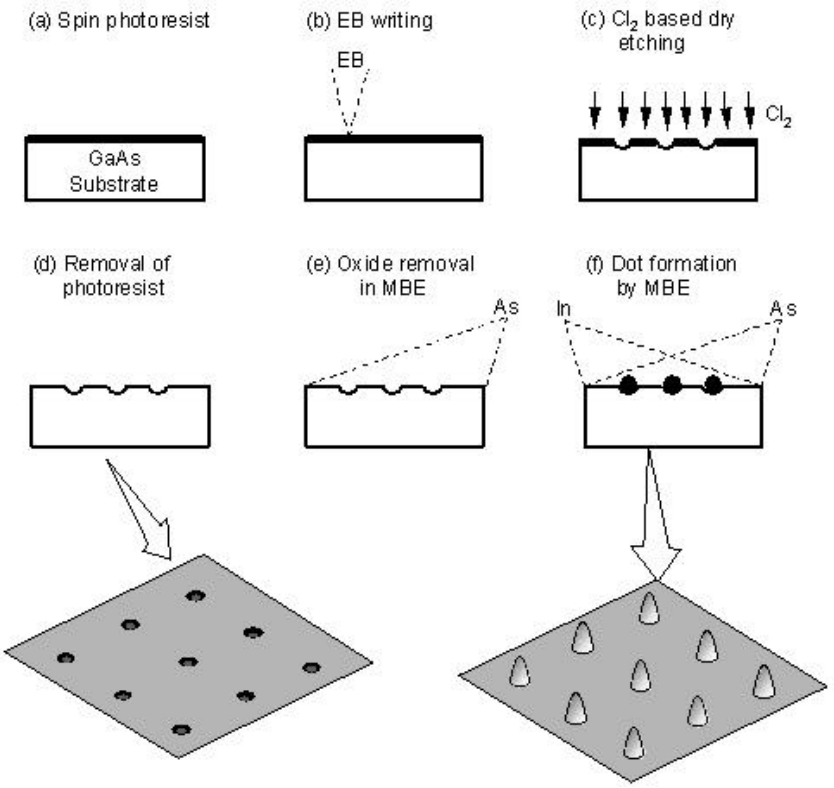

Figure 3. Fabrication process of InAs Q-Dots on a GaAs substrate using E-beam nanolithography and MBE growth.

Molecular beam epitaxy (MBE) has access to all of the myriad methods available to encourage the self-assembly of nano-crystalline structures. The method that has been the subject of intense study is the Stranski-Krastanov (SK) growth mode where islands develop on top of an initial wetting layer of strained material. This islanding process results in the formation of quantum dots. In this mode substrate temperature, III/V flux ratios, growth rate and the amount of strained material deposited all affect the size and density of the quantum dots formed [,]. Vertical alignment of quantum dots can also be achieved by growing a thin layer of substrate material to bury the quantum dots [ ]. Residual strain fields from the buried dots will determine the nucleation sites in the next layer of dots.

Figure 4. JPL newly installed 4-inch Molecular Beam Epitaxy machine (Applied EPI GEN III)

However, dots grown in the SK mode on standard (100) substrates exhibit very little lateral periodicity as well as an unacceptable degree of size variation. This size variation prevents the realization of photoluminescence (PL) line widths superior to those exhibited by quantum wells. Growth on pre-patterned (nano-structured) substrates should improve the PL line widths. As depicted in Fig. 3, strain relief and preferential nucleation on step-edges force the deposited material to only form islands in the pre-patterned holes.

These patterned substrates will be cleaned and introduced into the MBE chamber, where the native oxide will be thermally desorbed and quantum dots will be grown. Then post-growth analysis techniques such as atomic force microscopy, X-ray reciprocal space mapping, photoluminescence and FTIR spectroscopy will be used for characterization.

The technical objective of this year is to demonstrate a high-sensitivity long wavelength infrared (LWIR) QDIPs based on either on SK self-assembled material or the site and size controlled Q-Dots material developed in FY'03. The ultimate objective is to demonstrate a high performance, radiation hard, two-dimensional, QDIP focal plane array sensitive in the LWIR or MWIR spectral region. Fig. 5 shows the cross sectional view of the proposed QDIP device structure based on intersublevel photo-excitation in site and size controlled Q-Dots. The device structure will consist of 30-50 layers of vertically stacked Q-Dot layers sandwiched between two heavily doped GaAs layers. In order to suppress the dark current flowing through the bulk GaAs a thick undoped AlGaAs layer will be introduced in front of the collector. In addition, we are planning to incorporate a monolithically fabricated two-dimensional quasi-random grating reflector on the top contact layer, to enhance absorption quantum efficiency by taking advantage of the normal incident absorption of Q-Dots. The grating parameters will be optimized to trap the radiation via multiple reflections between the grating reflector and thinned substrate interface.

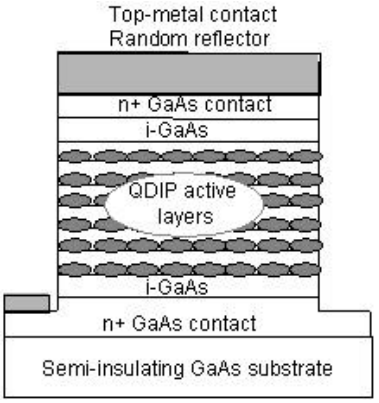

Figure 5. Cross-sectional view of the proposed QDIP device structure

4. References:

[i] G. S. Soloman et al., Appl. Phys. Lett. 66, 991 (1995).
[ii] G. S. Soloman et al., Appl. Phys. Lett. 66, 3161 (1995).
[iii] Q. Xie et al., Phys. Rev. Lett. 75, 2542 (1995)
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5. Accomplishments:

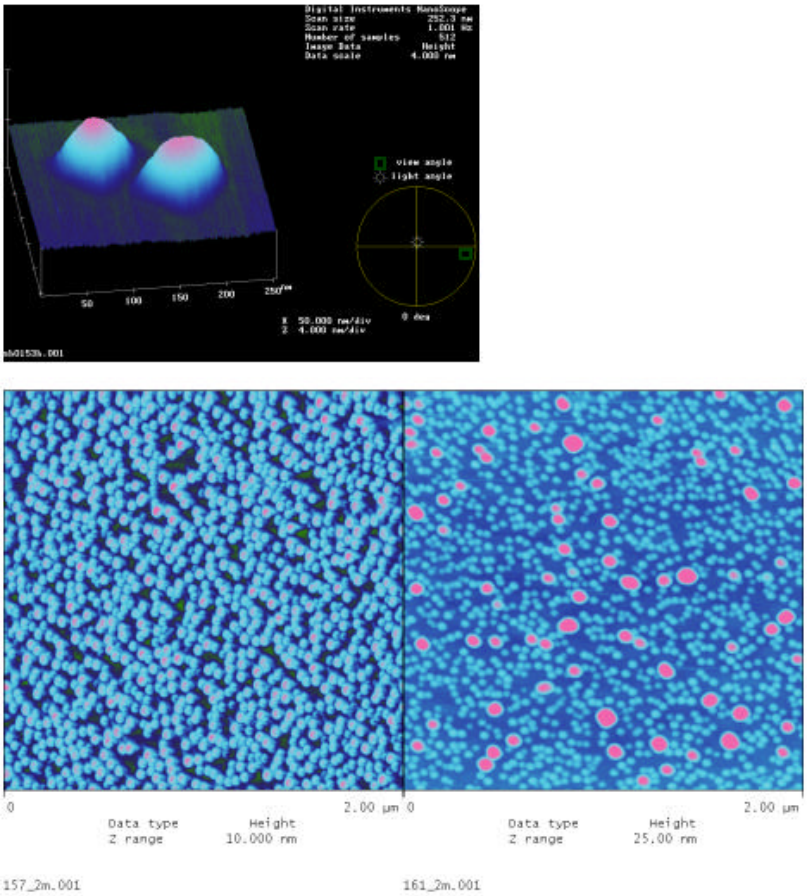
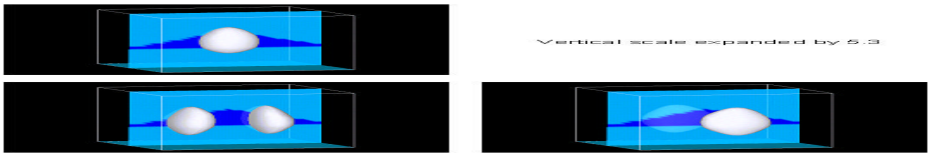


Figure 6. InGaAs and InAs QDOTs grown in GaAs substrates in MDL's new Veeco GEN III Molecular Beam Epitaxy (MBE) machine



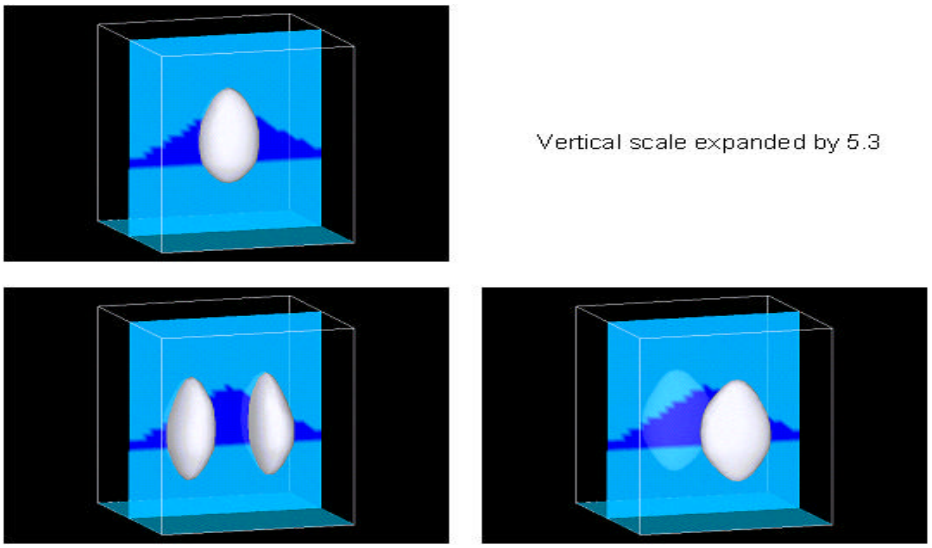
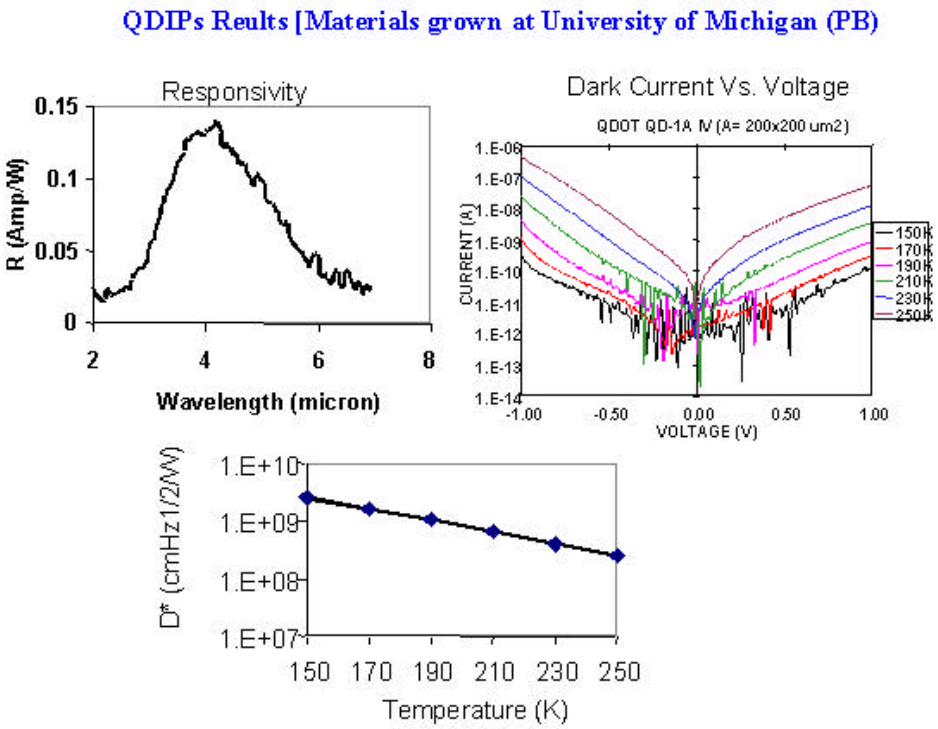


Figure 7. Wavefunctions of In0.5Ga0.5As dot embedded in GaAs pyramid. Base= 43 nm Height=2.8 nm, on 0.6 nm wetting layer.
Material Parameters
-In0.5Ga0.5As : Ec= -0.4415 m*=0.03428 m0
-GaAs : Ec= -0.315 m*=0.0673 m0



6. Publications:

"High-Temperature Operation of InAs/GaAs Quantum Dot Infrared Photodetector with Large Responsivity and Detectivity and Low NEAT",

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Submitted to IEEE Photonics Letters:

Collaborators:

Professor Pallab Bhattacharya - University of Michigan
Professor Bhattacharya's group provides us the stae-of-art QDOT device materials for infrared detector fabrication.

Professor Jimmy Xu - Brown University
Professor Xu'x group at Brown University has provided us site controlled nano-structured GaAs templates for QDOT growth at JPL.