11th International Conference on Advanced Materials
ICAM 2009
Rio de Janeiro Brazil
September 20 - 25

Focused Ion Beam Templating and Doping of Si/Ge Quantum Dot Nanostructures

J.F. Graham(1)*, C.D. Kell(1), J.A. Floro(1) and R. Hull(2)

(1) Dept. Materials Science & Engineering, University of Virginia, Charlottesville, Virginia, USA, e-mail: jfgraham@virginia.edu
(2) Dept. Materials Science & Engineering, Rensselaer Polytechnic Institute, Troy, New York, USA
* Corresponding author.

Abstract – The conventional Ga focused ion beam (FIB) has been previously used to template the growth of Si/Ge quantum dots (QDs). However, Ga is a *p*-type dopant in Si and can behave as a surfactant during epitaxial growth of Si and Ge. To avoid such issues in directed QD growth, this work utilizes a mass-selecting FIB and alloy sources to generate a range of ion beams beyond those available from elemental sources. Si and Ge ions are used to explore electrically non-invasive patterning and to investigate basic mechanisms in templated self-assembly. B and Mn ions are used for direct, nanoscale doping applications.

Self-assembled, epitaxial semiconductor quantum dots (QDs) have properties utilized in the design of potential nanoelectronic device architectures such as quantum dot cellular automata or magnetic spin switches. These devices rely on quantum mechanical behavior (e.g. charge tunneling or magnetic spin exchange between dots) and so require QD spacings and sizes on the order of nanometers to tens of nanometers. Epitaxial growth techniques can produce QDs with relevant sizes and suitable uniformity, but QD position is inherently random. In addition to their arrangement in complex, pre-determined patterns, QDs in a working device require electronic or magnetic functionalization. This research addresses the twin challenges of directed self-assembly and nanoscale doping of QDs using focused ion beams (FIBs).

Previous work has demonstrated templated growth of Ge QDs and SiGe quantum dot molecules (QDMs) on Si(100) surfaces pre-patterned using a conventional Ga^+ FIB.[1, 2] This work utilizes a mass-selecting FIB column (MS-FIB) and alloy ion sources, for example AuSi, AsPdB, and AuGeMn, to employ beams of ions otherwise unobtainable from elemental sources. We use non-invasive ions, ideally Si, but also Ge, for substrate patterning to avoid electronic and chemical effects inherent with Ga implantation (Ga is a *p*-type dopant in Si and can act as a surfactant during epitaxial growth of Si and Ge). Electronically non-invasive templating is clearly necessary for device fabrication. Templating with chemically non-invasive ions also opens new avenues for the study of fundamental mechanisms in templated QD growth.

Initial results using Si^{++} as the patterning ion do not demonstrate templating of QDMs or individual QDs; rather, a previously unobserved structure is nucleated only at low ion doses (see Figure 1). Ge ions, on the other hand, have a mass similar to Ga and so have a similar sputter yield meaning they are capable of creating the sputter induced topography seemingly necessary for directed QD and QDM nucleation. We show our results exploring non-invasive templating with Si and Ge ions and compare them to previous work using Ga ions.

We are also using our MS-FIB for nanoscale doping of QDs; for example, B and Mn ions are used for electronic and magnetic doping, respectively. Key issues include demonstrating sample recovery after FIB implantation and development of new alloy ion sources. Optical spectroscopy as well as low-temperature transport and magnetic characterization techniques are used to assess post-implant sample damage and dopant activation, following thermal processing.

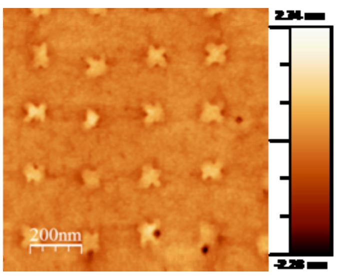

Figure 1: AFM image of templated nanostructures after growth of a 22.5 nm thick $Si_{0.7}Ge_{0.3}$ film on a periodic array patterned using a 5.5 pA $^{28}Si^{++}$ beam and 5 ms dwell.

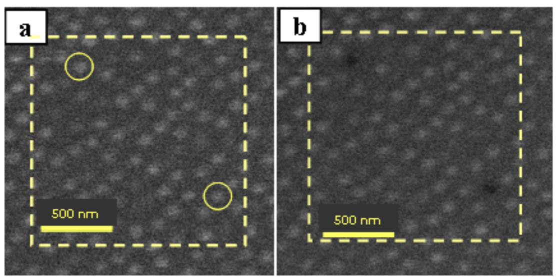

Figure 2: In-situ secondary electron images in our mass-selecting FIB of a field of Ge QDs on a Si(100) surface before (a) and after (b) targeting of individual QDs with a 1 pA $^{11}B^+$ beam with a 0.25 s dwell (exposures can be < 1 µs).

References
[1] A. Portavoce, R. Hull, M. C. Reuter, et al., Physical Review B 76 (2007) 235301
[2] J. L. Gray, R. Hull, and J. A. Floro, Journal of Applied Physics 100 (2006) 084312