Precise Positioning of Quantum Dot Molecules by Directed Self-Assembly

by **J. A. Floro**

Motivation—In order to overcome the fundamental limits that will prevent continued shrinking of microelectronics, revolutionary new quantum computing schemes will be needed within the next two decades. However, if we are to realize the extraordinary information processing potential offered by quantum logic, control at near-atomic length scales is required to build devices based on ordered assemblies of nanoscale quantum dots. While such structures are well beyond the capabilities of standard lithographic techniques, *directed self-assembly* approaches are already demonstrating how complex 3D nanostructures can be constructed via manipulation of the natural processes associated with their growth. We self-assemble quantum dot nanostructures by exploiting intrinsic strain relaxation processes during heteroepitaxial growth of thin SiGe alloy films on Si substrates. This growth/materials strategy is well aligned with current device fabrication procedures, making its acceptance by the microelectronics industry far more likely than other techniques for quantum dot production.

Accomplishment—While existing research has emphasized formation of individual quantum dots, we have extended our investigations to self-assembly of quantum dot *molecules*, (QDMs) — size-selecting nanostructures consisting of four quantum dots elastically bound together by a central "anti-dot". QDMs normally self-assemble at random locations, as shown in Fig. 1, which is incompatible with nanologic device requirements. This year we have shown that QDMs can be precisely located using patterns established *ex situ* by focused ion beam (FIB) treatments of a Si substrate. The FIB was used to create periodic arrays of nanoscale holes in the Si, with varying depths and spacings, as shown in Fig. 2. These patterned substrates were then subjected to our standard, kinetically controlled, growth regimen for SiGe on Si that produces QDMs on unpatterned substrates. By controlling the Si buffer layer thickness and the FIB dose, we can precisely locate QDMs in one-to-one correspondence with the FIB hole array, as shown in Fig. 3 for several pattern spacings. Note that a one-to-one correspondence of QDMs to FIB features actually represents a four-to-one correspondence of quantum dots to FIB features, which is efficient. Very small FIB doses can be used to locate QDMs, but "missing pixel" errors start to crop up at low dose. While we observe spurious nucleation of QDMs on the patterned substrates, this is minimized by reducing ion dose and increasing pattern density.

Significance—The ability to put QDMs where we want them is critically important to their application in quantum computing. An example is the use of QDMs in a logic architecture based on *quantum cellular automata (QCA)*, which requires the use of four-fold QDMs (acting as charge-switching logic elements) arranged in specific patterns. QCA logic relies on electrostatic interactions and therefore does not require interconnects between the individual QDMs, as long as proper positioning, size-selection and spacing can be achieved. Our directed self-assembly process results in pre-specified patterns of elastically bound, four-fold quantum dot structures that exhibit narrow size distributions. Hence we are already achieving many of the critical requirements for self-assembly of semiconductor QCA.

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences and National Science Foundation

Contact: Jerrold A. Floro, Surface & Interface Sciences, Dept. 1114
Phone: (505) 844-4708, Fax: (505) 844-1942, E-mail: jafloro@sandia.gov

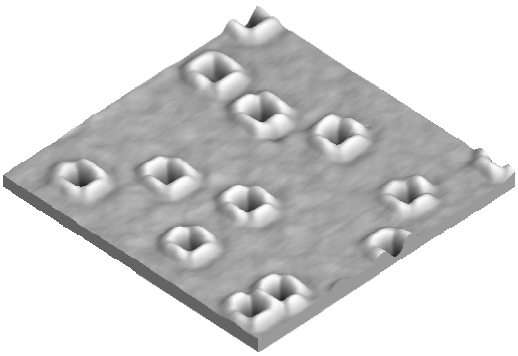

Figure 1. Heteroepitaxial QDMs in $Si_{0.7}Ge_{0.3}$ on unpatterned Si. Atomic force microscope image, 2x2 µm.

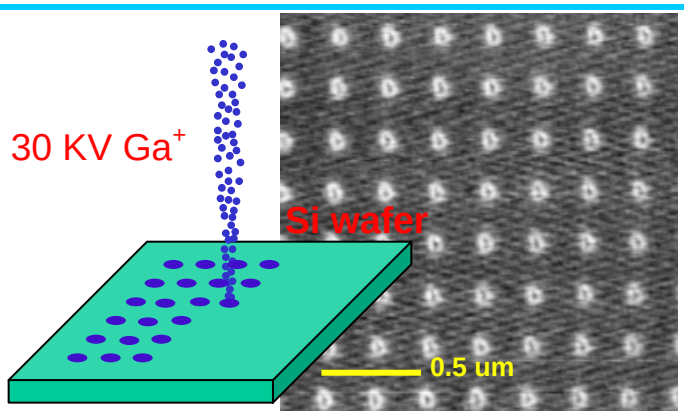

Figure 2. A focused ion beam is used to write an array of shallow, nanoscale holes in a Si wafer, as shown schematically. An atomic force microscope image of an actual hole array is also shown.

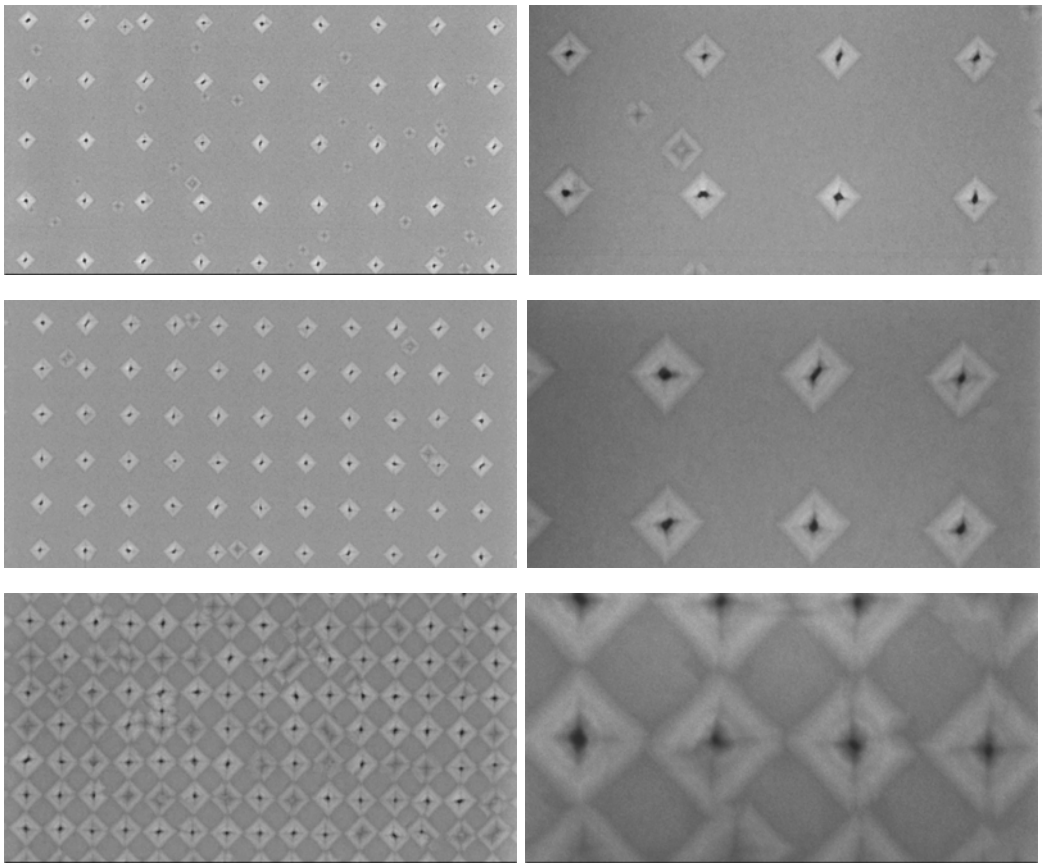

Figure 3. $Si_{0.7}Ge_{0.3}$ QDM arrays on FIB-patterned Si, at low (images on left) and high (images on right) magnification. Upper panel: 0.75 µm feature spacing; middle panel: 0.5 µm feature spacing; lower panel: 0.25 µm feature spacing. Scanning electron microscope images.