

Size Selection in Self-Assembled Quantum Dot Molecules for Nanologic Devices

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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) which consist of four quantum dots elastically bound together by a central "anti-dot", as shown in Fig. 1. This year we have demonstrated that QDMs prefer a narrowly selected lateral size. Figure 2 shows a statistical summary of the size distributions of QDMs formed of strained $\text{Si}_{0.7}\text{Ge}_{0.3}$, where both thickness variation and annealing have been employed in order to test the tendency to size select. The result is remarkable—QDMs form the same preferred lateral size

even when film thickness is increased by more than 200%, or during annealing for times up to 1600% longer than the QDM growth time. Through experiment and modeling we have obtained a heuristic understanding of the origins of size selection. We find that size selection is not thermodynamic; indeed, when annealing temperatures are raised sufficiently, the QDM structure completely breaks down. Instead, QDMs size select due to kinetic limitations associated with the growth conditions. Two factors are at work. First, there is an intrinsic length scale due to the competition between strain and surface energy that governs the formation of the precursor QDM structure. Second, we find that QDM growth stops completely when the four dots coalesce to form a continuous ring. This ring effectively traps atoms inside, elastically preventing their escape from the central anti-dot region, thereby suppressing QDM enlargement.

Significance—Size selection in QDMs is critically important to their ultimate application in quantum computing. An example is the use of a QDM in a logic architecture based on quantum cellular automata, which requires the use of four-fold QDMs (these are the charge-switching logic elements) that are size-selected (in order to have uniform electronic properties). In collaboration with University of Virginia and Notre Dame University, we have begun exploring the use of our kinetically self-assembled QDMs in this exciting application. Figure 3 shows a SiGe QDM that is being "wired-up" to external test circuitry. Further improvement of our science-based control over these structures may enable a significant advancement in the development of quantum-logic computers.

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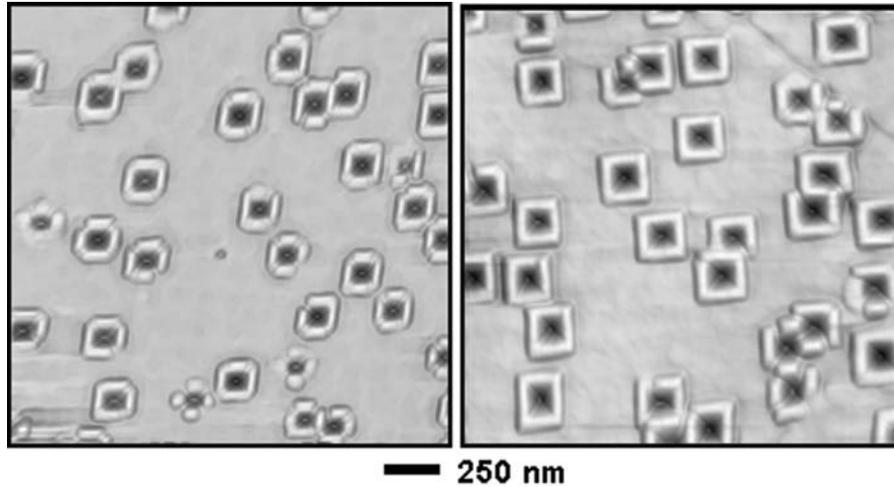


Figure 1. Heteroepitaxial QDMs in $\text{Si}_{0.7}\text{Ge}_{0.3}/\text{Si}$ at 200 Å (left) and 300 Å (right) film thickness.

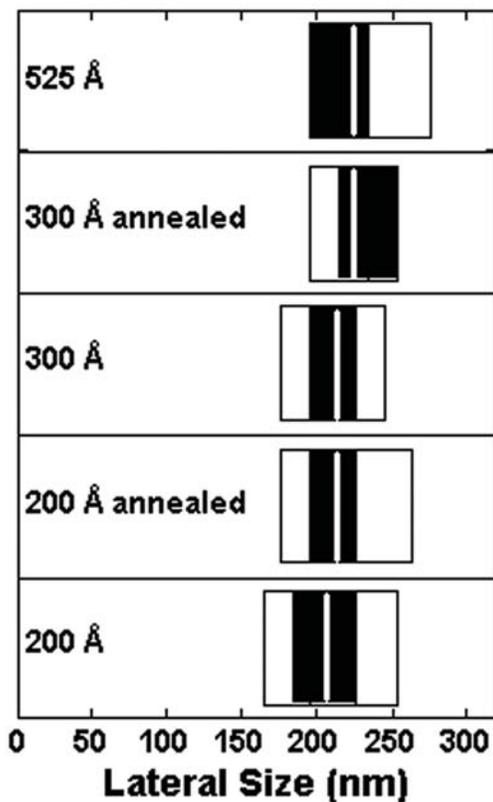


Figure 2. A percentile plot summary of the size distributions for $\text{Si}_{0.7}\text{Ge}_{0.3}$ films of different thicknesses, with and without annealing. Each open box encloses the inner 90% of the data, each filled box encloses the inner 50% of the data, and the white bar represents the mean.

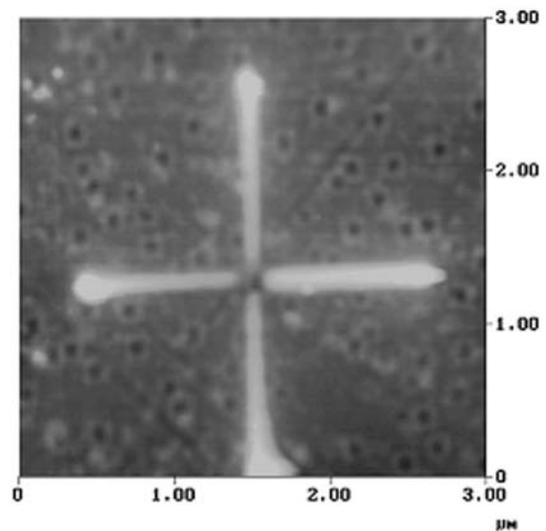


Figure 3. Platinum leads written onto a single QDM using focused ion beam techniques (in collaboration with G. Snider, Notre Dame, and R. Hull, UVa).