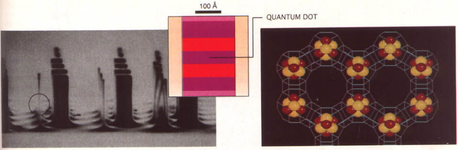

What Isu would like to know is why the clumps appear at random locations and what effect they have on the uniformity of the crystal layers.

"Nobody knows how molecular-beam epitaxy actually occurs, how the layers of gallium and arsenic combine," observes Izuo Hayashi, director of the lab and one of the inventors of the semiconductor laser. He believes that before highly confined devices such as quantum wires and dots can be routinely fabricated, researchers must improve their understanding of what happens on an atomic level during epitaxial growth and etching.

Efforts to build quantum wires and dots continue, nonetheless. Many investigators are trying the same techniques they use for making quantum wells. But because a quantum wire or dot is significantly smaller than a quantum well, bombarding a material with ions can ravage the crystal lattice.

As a result, researchers are looking for other approaches. "Rather than just cutting [etching through the semiconductor], we need to make use of some natural tendency of the material," Hayashi says. His team would like to control the edges of atomic layers as the material grows in an MBE. Yet success has remained just out of reach.

Many groups are trying different schemes. Pierre M. Petroff, Arthur Gossard and their colleagues at the University of California at Santa Barbara, for instance, grow quantum wires in an MBE by stacking elements, one atomic layer at a time, on terraced steps in a semiconductor substrate. This technique produces vertical—or often, tilted—quantum wells measuring 50 angstroms on a side, which can be made into quantum wires. It nonetheless requires agonizing precision. More recently they have tried continuously changing the time that each atomic layer is allowed to grow on the surface so that the resulting layers snake back and forth rather than lining up in straight or tilted stripes. In this "serpentine superlattice," the quantum wires are formed at the bends of the curves, resulting in more uniform arrays of wires than early techniques afforded.

Others have developed variations on etching. Eli Kapon and his colleagues at Bellcore created a V-shaped groove in a semiconductor substrate, then deposited a lower band-gap material in the base of the V. Kapon's team has even built lasers from one to three quantum wires. Such lasers churn out light when powered with only .65 milliamp at room temperature, an extremely low laser threshold.

At the University of Stuttgart, B. E. Maile and his colleagues traced a pattern of wires onto a substrate using reactive-ion beams, cleaned the wires carefully with a chemical solvent and then "buried" the wires by covering them with a semiconductor layer using a deposition technique akin to MBE called metallorganic vapor-phase epitaxy (MOVPE).

Nevertheless, investigators continue to debate whether these techniques—or any other ones—have yielded the distinct splitting of electron energies that should characterize a quantum wire. Most of these wires are too thick. The larger the devices, the smaller the energy splittings, and the harder to say conclusively: this is a quantum wire.

The Zero Zone

At the end of the quantum rainbow are quantum dots. These are often called artificial atoms, even though the particles may consist of thousands or hundreds of thousands of atoms. Confined in a dot, or box, electrons should occupy discrete energy levels. It should be possible, therefore, to dial up precise energy levels by adjusting the construction of the quantum box and by varying the applied voltage.

On the edge of central Tokyo, amid weeds and straggly trees, is the unkempt Komaba research park, a part of the University of Tokyo. In a modest, two-story brick building built some 60 years ago is Yasuhiko Arakawa's laboratory. As is traditional in Japanese homes, visitors entering Arakawa's laboratory slip off their shoes and don plastic sandals. But there is another reason for changing footwear; around the corner from Arakawa's spartan office is a high-quality clean room packed with $10 million in equipment for building quantum devices.

In 1982 Arakawa and his mentor Hiroyuki Sakaki proposed the concept of quantum boxes, or dots. They have yet to construct a working set, however. "It is very difficult to realize a real quantum box with 100-angstrom spacing [along all six sides]," Arakawa says. "Nobody has succeeded in fabricating a real quantum box laser," he insists.

Indeed, making quantum dots with semiconductor technology seems an exercise in exponential complications. Processing complexity increases "in some nonlinear way," says Kathleen Kash, a researcher at Bellcore. Stating that a dot "works" guarantees controversy. And a single dot on its own is not particularly useful. Investigators must find ways to manufacture collections of dots and then to integrate them into devices.

Chemists, however, have had extraordinary success in making quantum dots—although not ones yet suitable for devices. In his office at Bell Labs, Michael L. Steigerwald keeps a collection of small vials. Each is filled with a vividly colored powder—yellow, orange, red, black. "They're all cadmium selenide," he says, almost with awe. Each vial holds different-size clusters—essentially quantum dots—of cadmium and selenide atoms.

The different-size clusters have unusual physical properties, such as in-