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arrays. Lasers, semiconductor Quantum wells

QUANTUM WIRE AND QUANTUM DOT SEMICONDUCTOR LASERS

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ABSTRACT

There is currently great interest in fabrication of structures that are two and three dimensional analogs of the conventional quantum well. We review here the physics behind the use of arrays of such lower dimensional structures in semiconductor laser active layers. Methods which are currently under investigation for producing such structures will be discussed.

Quantum wires and quantum dots are two and three dimensional analogs of the conventional quantum well (see Figure 1). A quantum dot, for example, would confine an electron in three dimensions to a size comparable to the de Broglie wavelength of the electron in the crystal. To be useful in a device, arrays of quantum wires and quantum dots must be considered as illustrated in Fig. 1. In such arrays quantum dots and wires composed of a low bandgap material would be imbedded in a higher bandgap host (e.g., GaAs dots in an AlGaAs host). A potentially important application of these structures is to laser diodes.[1] In such devices, the conventional bulk active layer is replaced with an array of quantum dots or quantum wires. As discussed below, these devices would have many advantages over conventional devices.

The most important property of quantum wires and quantum dots as concerns their application to laser diode active layers is their density of states functions. Idealized versions of these functions are presented in Fig. 2 for bulk, conventional quantum well, quantum wire, and quantum dot active layers. In reducing dimension it is apparent that these functions take on more singular behavior. For the quantum dot, the behavior is analogous to the density of states of an atomic system. This narrowing of the density of states function carries over directly into the optical gain spectrum, which, for k-conserving transitions, is proportional to the effective density of states of the electronic system and the Fermi

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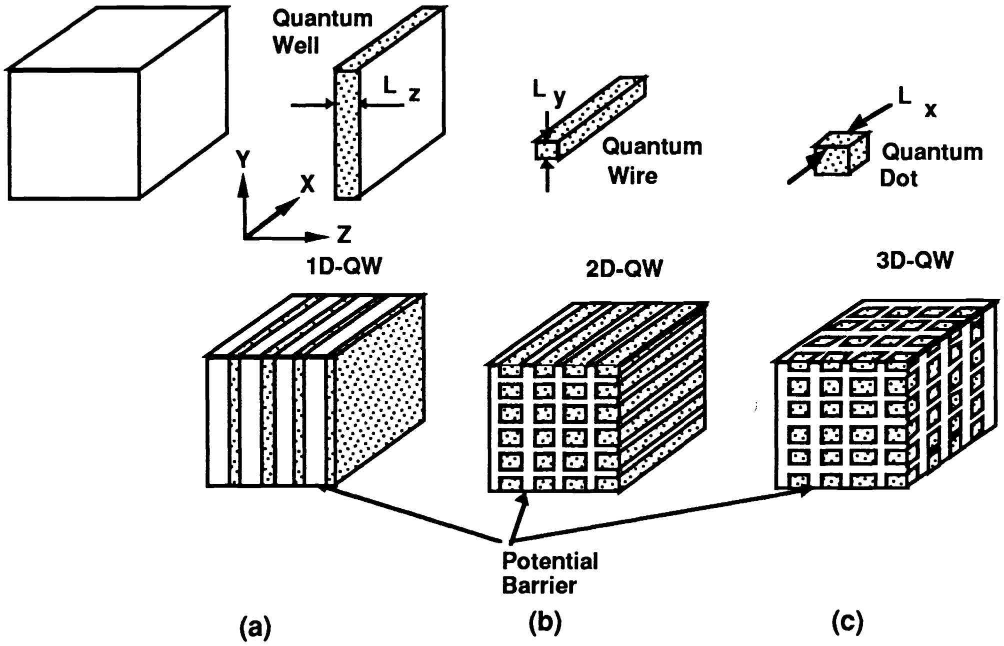

Fig. 1. Schematic drawing of quantum wells, wires and dots showing the successive dimensions of confinement. The lower part of the figure shows arrays of these structures suitable for incorporation into the active layer of a semiconductor laser. The structures are formed from low bandgap material imbedded in a higher bandgap host.

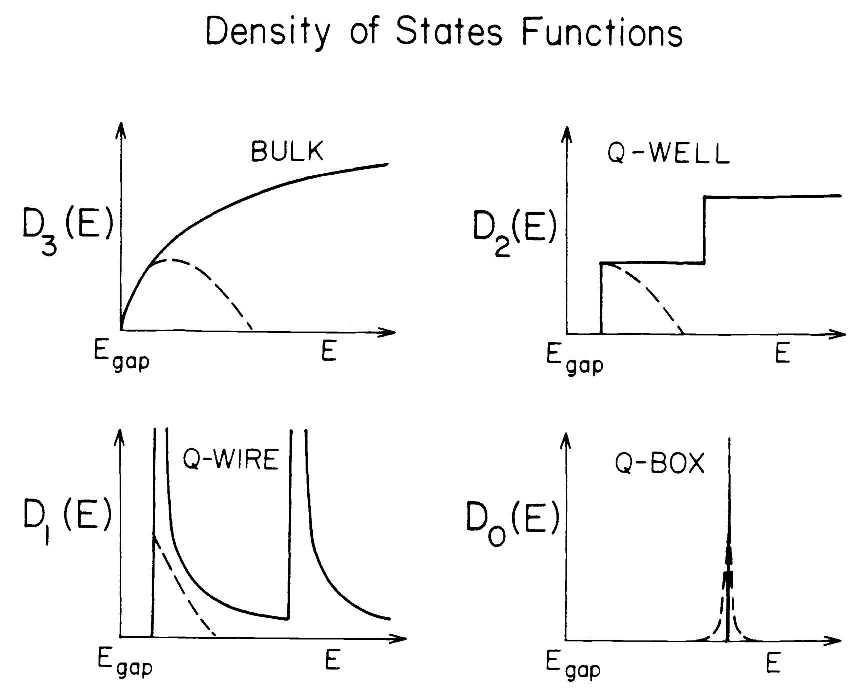

Fig. 2. Density of states functions for zero-, one-, two-, and three-dimensional systems. The dashed curve indicates approximately the optical gain which results when the medium is inverted.

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occupancy factor giving the strength of the inversion. The dashed curves appearing in Fig. 2 show typical gain spectra for each case. Gain spectrum narrowing is maximum for the quantum dot. In fact, here the gain spectrum width is zero according to this highly simplified model.(In a more realistic model phonon scattering broadens the transition leaving a Lorentzian lineshape as has been illustrated in the figure.)

A laser based on a narrower gain spectrum has many advantages.[1,7] First, it is clear that lower threshold currents are possible since fewer carriers are wasted in regions of the spectral space that are not contributing to lasing action. It is important to note that there is also a significant reduction in the transparency excitation level of the gain medium simply from the reduction of the active layer volume. The resulting reduction in threshold has been exploited in ultra low threshold conventional quantum well semiconductor lasers and can also be exploited in quantum wire and quantum dot semiconductor lasers.

Dynamic and spectral properties are also improved in these devices. Consider, for example, the direct modulation speed of a diode laser as determined by the relaxation oscillation corner frequency. The square of this corner frequency is easily shown to vary linearly with the differential gain (i.e., the derivative of gain with respect to carrier density). Differential gain will, roughly speaking, vary inversely with spectral width. Hence, reduced dimension results in higher modulation speeds.[1] Using similar arguments it is possible to show that chirp reduction, phase noise reduction, and intensity noise reduction also can result from the reduction of the active layer electronic system dimension.[1] The application of quantum well and quantum wire active layers to phase noise reduction and modulation speed enhancement in laser diodes was first discussed in Reference 1. All of the theoretical predictions concerning conventional quantum well active layers have since that time been verified.

The fabrication of quantum wires and quantum dots poses many challenging problems. At the present time there are two general approaches being taken. Historically first are a variety of techniques in which a quantum well which has been grown on a substrate is modified for lateral confinement on a nanometer scale. In all of these techniques a nanometer scale pattern is first generated on the sample using lithographic methods such as electron or ion beam lithography. The techniques then diverge in terms of how this pattern is transferred to the quantum well resulting in a quantum wire or a quantum dot. One simple example of this could be referred to as the "cookie cutter" approach. In it the lateral confinement is produced by actually etching away unmasked regions of the quantum well sample.[2,3] Although extremely small structures are possible with this approach, the resulting structures suffer from free surface induced nonradiative recombination. Recent efforts in this direction are addressing the issue of surface passivation either by chemical treatment or by actual regrowth on the etched structures. A more sophisticated pattern transfer technique that does not leave behind free surfaces is based on disordering of the quantum well either by ion implantation[4] or by diffusion.[5] These techniques have produced convincng results and are illustrated by the example in Fig. 3. Here again a mask is patterned onto the surface of a semiconductor, containing in this case a shallow quantum well. The mask is patterned using electron beam lithography and subsequently arrays of silicon lines are deposited in a liftoff process. The silicon then serves as a mask in a shallow zinc diffusion into the quantum well. The diffusion of zinc is known to abruptly disorder a

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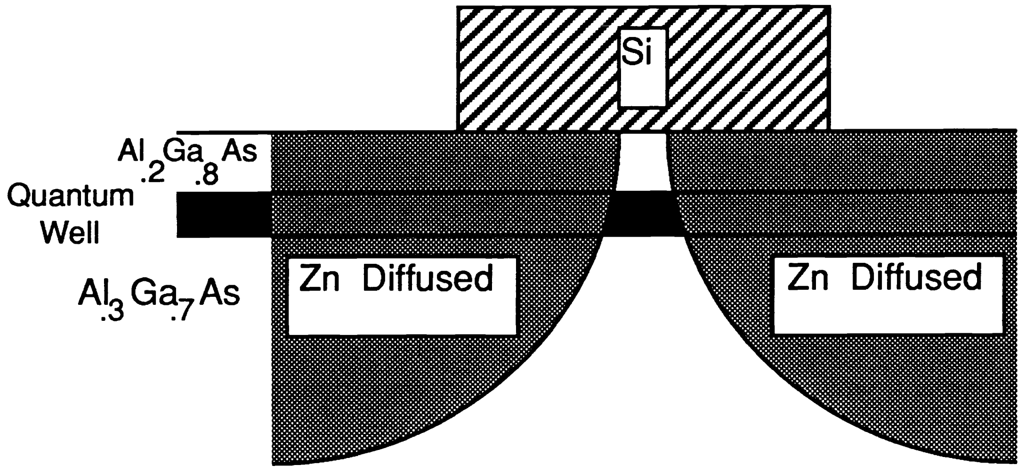

Fig. 3. A schematic drawing of diffusion induced disordering of a shallow quantum well to produce quantum wires. A narrow stripe of silicon is produced by electron beam lithography and subsequent liftoff on the surface of a sample containing a shallow quantum well. The silicon stripe serves as a mask for a zinc diffusion which selectively disorders the quantum well.

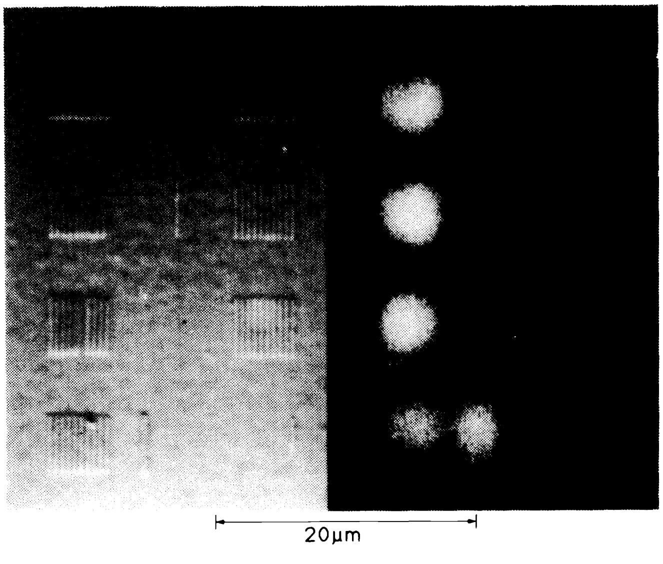

Fig. 4. Secondary electron and cathodoluminescence images of several arrays of wires and an isolated wire. The left half shows the silicon mask as a conventional SEM micrograph. The width of the silicon stripes in the arrays varies from 3700Å (upper left array) to 1600Å (lower right array). The right half shows the spectrally resolved cathodoluminescence image of the same region at a wavelength of 780 nm. The sample temperature is 77K.

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quantum well. By timing the diffusion correctly, wire-like regions of low bandgap quantum well material are left behind. Fig. 4 shows a scanning electron micrograph of several silicon arrays with elements of various widths.

Also shown in the figure is a cathodoluminescence (CL) micrograph of this same region of the sample. Cathodoluminescence is an alternative means of imaging with a scanning electron microscope. Rather than collecting secondary electrons, CL uses light that is emitted by the recombining electron-hole pairs that have been excited by the electron beam.[6] The collected CL emission in this micrograph is spectrally resolved using a grating monochrometer before detection. The wavelength selected is slightly blue shifted from the original quantum well emission peak. The CL image indicates that the quantum well has been successfully disordered in the unmasked regions of the sample. The inability to actually resolve the lines is a consequence of CL's limited spatial resolution which is determined by carrier diffusion.

Before discussing the second category of fabrication approaches, it is interesting to consider again the application of these structures to semiconductor laser active layers. In addition to the considerations mentioned earlier, we will now include an additional non-ideality that plays a central role in determining the ultimate performance of a quantum wire or quantum dot semiconductor laser. This is fabricational inhomogeneity. Consider, for example, arrays of quantum dots. The confinement energy depends strongly in these structures on the size of the dot. This, in turn, implies that the gain spectrum for an array of quantum dots experiences fabricational induced inhomogeneous broadening. Such broadening tends to counteract the beneficial effects of quantum confinement. The interesting question is therefore: what fabricational tolerance is required if a quantum dot active layer is to outperform a conventional active layer? This question is addressed in Fig. 5 where maximum attainable gain (in both inverse spatial and temporal units) has been plotted for various densities of GaAs quantum dots versus a fabricational RMS variance in dot diameter.[7] There are actually two sizes of dots considered in the plot. Large dots having a radius of $100\AA$ and small dots having a radius of $50\AA$. Consider the case of small quantum dots with a packing density $\eta_s = 1.25 \times 10^{17} cm^{-3}$. To attain a maximum optical gain of 120 cm^{-1} (a number typical of bulk GaAs material under high excitation) all dots must be filled with two electrons and two holes (i.e., the equivalent carrier density will be $2.50 \times 10^{17} cm^{-3}$) and a fabrication tolerance of $20\AA$ must be maintained. This is well over an order of magnitude better than the bulk material which would only attain these values at carrier densities on the order of $5 \times 10^{18} cm^{-3}$.

There are two important points to be made here. First, the above estimate is good news for approaches based on nanolithographic patterning, because although a $20\AA$ tolerance on an array of $200\AA$ diameter dots exceeds the current state-of-the-art in beam patterning and pattern transfer, it is well within an order of magnitude of what is currently attainable. Second, in considering the figure, it is clear that what is truly needed is a fabrication technology capable of monolayer tolerences, i.e., the equivalent of MBE or MOCVD in the lateral directions.

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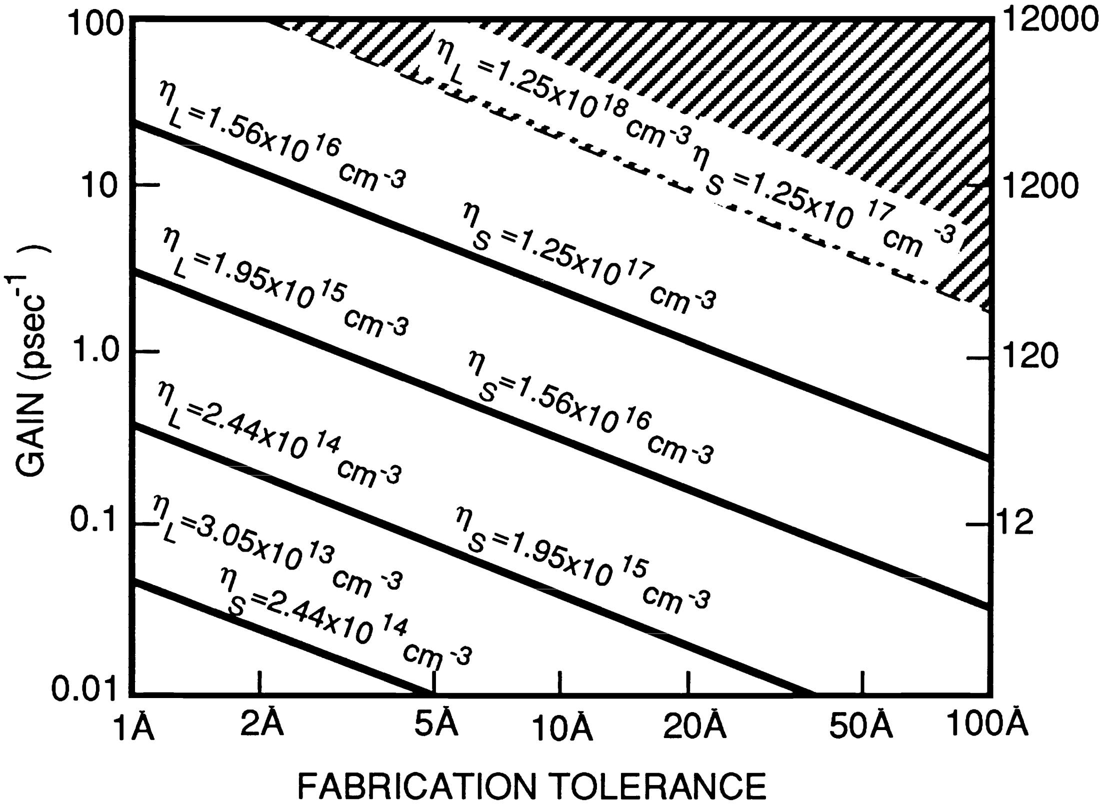

Fig. 5. Maximum possible optical gain versus fabrication tolerance(given as the rms roughness of dot diameter) for arrays of quantum dots of various dot densities(η_L,η_S). Large quantum dots (density η_L) will have an average diameter of 200Å and small quantum dots (density η_S) have an average diameter of 100Å. The cross hatched region is beyond the geometrical packing limit of the quantum boxes.

Although such a technology does not yet exist, the second category of techniques are clearly moving in this direction. These are techniques that seek to extend the fabricational control offered by MBE and MOCVD in the z-direction into the x and y-directions. In this way the quantum wires or dots can be formed in the growth process. Examples of these techniques are vicinal growth to produce vertical superlattices[8], quantum well thickness control through growth on patterned substrates[9], and very recently compositional control through growth on patterned substrates.[10] Fig. 6 illustrates the latter of these. The top of Fig. 6 shows a schematic drawing of a substrate patterned by chemically etching a groove. MBE growth of AlGaAs epilayers on such a substrate proceeds along various directions. Surprisingly, under appropriate growth conditions, it has been demonstrated that the (111) growth directions segregate into a quasi periodic structure having a period between 50 – 70Å.[10] On the average the composition is uniform, but the microscopic ordering along

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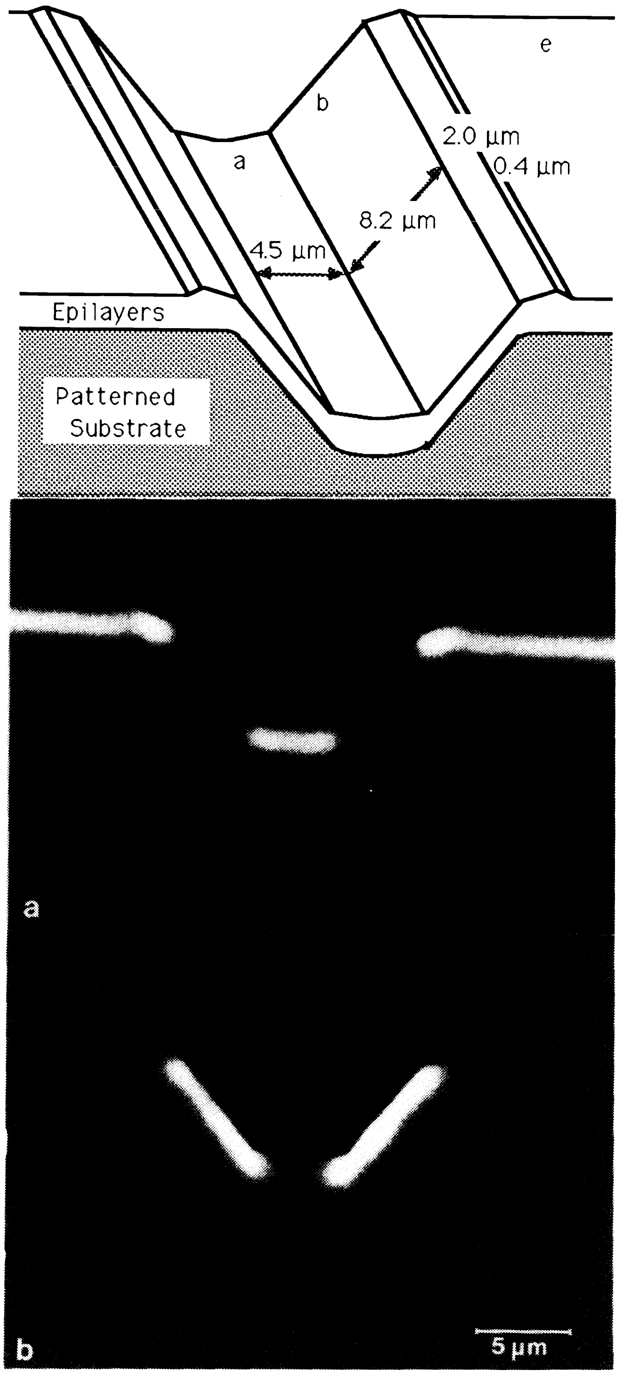

Fig. 6. Spectrally resolved cathodoluminescence micrographs of a cross section of a groove in the surface. A schematic diagram of the grown sample is shown at the top. The different micrographs represent luminescence images of the sample taken at particular wavelengths. (a) 6700Å and (b) 7000 Å.

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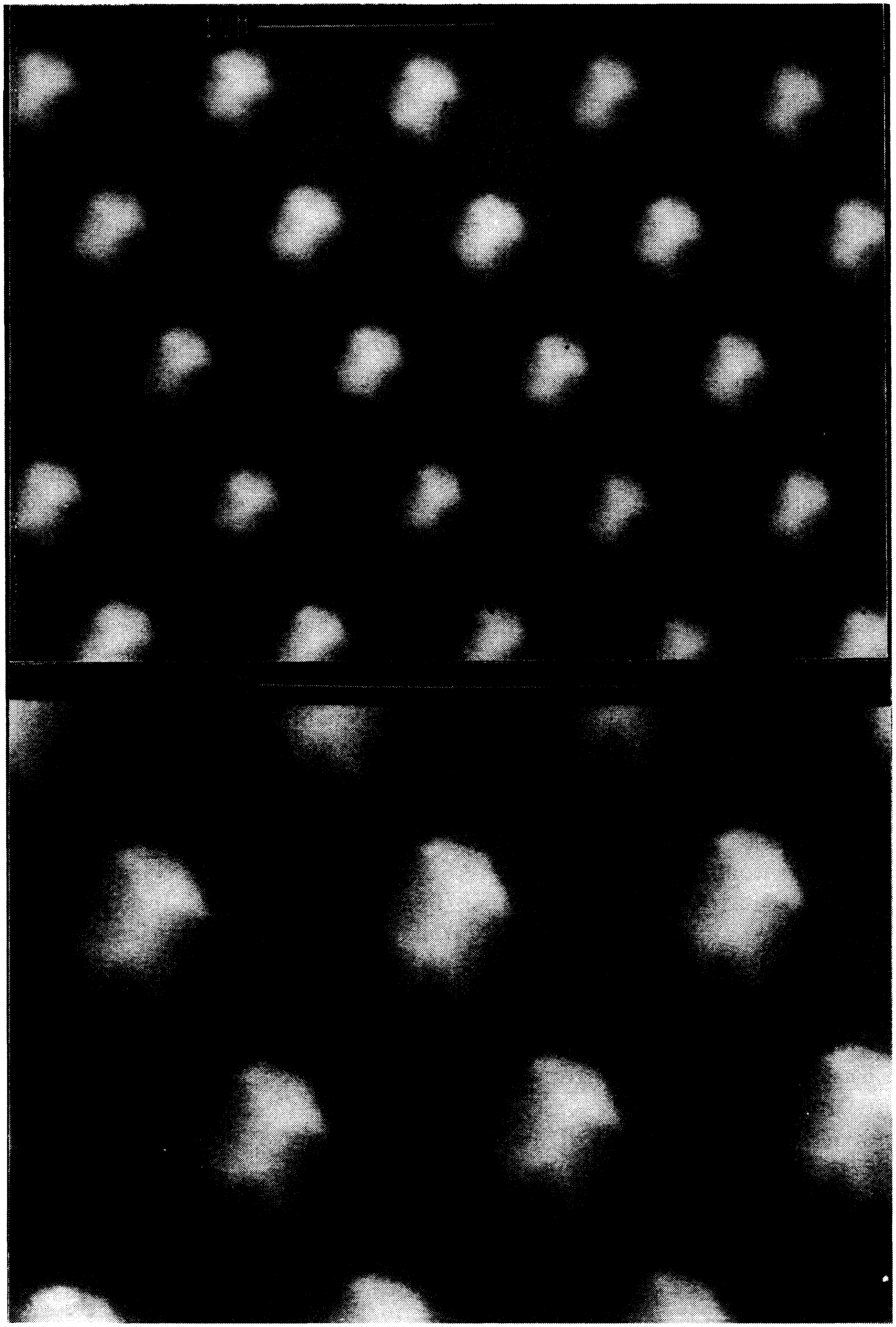

Fig. 7. SEM micrograph of selectively grown GaAs dots showing faceted nature of growth.

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the (111) growth directions produces an abrupt lateral change in the effective bandgap energy. This is apparent in Fig. 6 where CL micrographs of groove crossections are shown at two different wavelengths.

A new technique which we are currently pursuing is the use of selective epitaxy to grow quantum dot and quantum wire structures.It is related to the above techniques in that the dot structure is formed during growth. It is also related to beam patterning methods descibed earlier since the positions at which the dots or lines are grown is patterned prior to growth. Selective epitaxy refers to a lateral spatially controlled growth of an epitaxial material within openings of a mask material residing on the substrate during growth. The masking material we use is a dielectric layer of Si 3N 4. Recent optimization of growth conditions and selection of growth precursors have produced the high quality growth of GaAs in openings down to the micron scale[11]. By using electron beam lithography to generate the openings we have successfully grown structures with diameters less than 700Å. Fig. 7 shows an SEM micrograph of .25μm GaAs dots grown by this method. These photos illustrate the facetted nature of the growth.By performing a subsequent growth of AlGaAs these GaAs structures can be completely imbedded in a higher bandgap material. We have recently achieved such growth and have seen luminescence from GaAs dots less than 1000Å in diameter.

In conclusion, the optical properties of arrays of quantum dots and quantum wires have been discussed with emphasis on their application to semiconductor lasers. In addition, a number of approaches to fabrication of these structures have been discussed. Fabrication approaches currently under investigation divide into two broad categories: fabrication based on beam patterning and *in-situ* fabrication approaches. Extremely good control of fabrication tolerance is essential if quantum wires and quantum dots are to be be useful in semiconductor lasers. With continued refinements in existing fabrication techniques useful quantum wire and quantum dot semiconductor lasers should be possible. To fully tap the performance advantages of these structures, however, will probably require an entirely new fabrication technology.

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