

quantum wells by electrical means and have the potential for producing population inversion and gain in a solid-state device in the far infrared.

REFERENCES

1. M. Helm, P. England, E. Colas, F. DeRosa, and S.J. Allen, Jr., *Phys. Rev. Lett.* **63**, p. 74, 1989.
2. L. Esaki and R. Tsu, *IBM J. Res. Dev.* **14**, p. 61, 1970.
3. R.F. Kazarinov and R.A. Suris, *Fiz. Tekh. Poluprovodn.* **5**, p. 797, 1971; *Sov. Phys. Semicond.* **5**, p. 707, 1971; **6**, p. 148, 1972; **6** p. 120, 1972.
4. A. Seilmeier, H.J. Hubner, G. Arbstreiter, G. Weimann, and W. Schlapp, *Phys. Rev. Lett.* **59**, p. 1345, 1987.
5. D.Y. Orbeli, D.R. Wake, M.V. Klein, J. Klem, T. Henderson, and H. Morkoc, *Phys. Rev. Lett.* **59**, p. 696, 1987.
6. L.C. West and S.J. Eglash, *Appl. Phys. Lett.* **46**, p. 1156, 1985.
7. M. Helm, E. Colas, P. England, F. DeRosa, and S.J. Allen Jr., *Appl. Phys. Lett.* **53**, p. 1714, 1988.
8. L. Esaki and L.L. Chang, *Phys. Rev. Lett.* **33**, p. 495, 1974.
9. K.K. Choi, B.F. Levine, R.J. Malik, J. Walker, and C.G. Bethea, *Phys. Rev. B* **35**, p. 4172, 1987.
10. T.H.H. Vuong, D.C. Tsui, and W.T. Tsang, *Appl. Phys. Lett.* **52**, p. 981, 1988.

Semiconductor quantum wire lasers

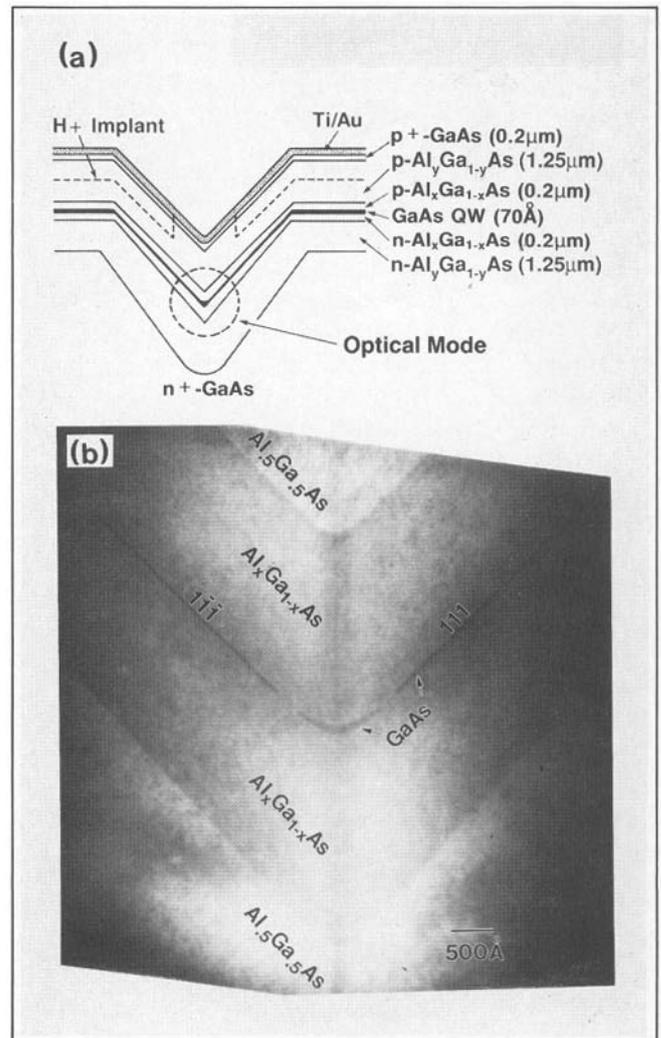
E. Kapon, Bellcore

The performance of semiconductor lasers has been improved by the use of quantum confinement in one dimension. In these conventional quantum well (QWL) lasers, the charge carriers recombine and emit light in extremely thin (usually less than 100 Å) layers of a lower band gap semiconductor such as GaAs cladded by a higher band gap barrier compound, e.g., AlGaAs. The quantum confinement of carriers in the direction normal to the QWL plane gives rise to discrete energy levels, which effectively narrows the spectral profile of the optical gain. This, in turn, leads to lower threshold currents, higher modulation bandwidths, narrower spectral linewidths, and reduced temperature sensitivity.

The development of semiconductor laser structures that use quantum confinement in more than one dimension is expected to yield further improvement in their performance and to provide new insight into the physics of low-dimensional semiconductors. Two-dimensional (2D) quantum confinement can be achieved with so-called quantum wire (QWR) heterostructures, in which a thin wire (a few hundred Å or less in diameter) of low band gap semiconductor is embedded in a high band gap compound. However, interface quality is a major problem in these quantum structures. Interface defects formed during

the fabrication process reduce the radiative carrier lifetimes, which can inhibit the formation of the high carrier densities needed for lasing. Early attempts to make QWR lasers consisted of etching narrow mesas in conventional QWL laser material and regrowing high band gap semiconductor material around the etched features to passivate the surface.² These lasers, however, operated only at low temperatures and the lateral dimensions of the wires were too large to produce observable lateral quantum size effects.

Recently, new techniques for making "buried" quantum wires that avoid exposure of the wire interfaces during fabrication have been developed. Molecular beam epitaxy of GaAs/AlGaAs quantum wells on the stepped sur-



Cross sections of a semiconductor quantum wire laser. (a) Schematic illustration, (b) transmission electron micrograph.

face of tilted substrates results in preferential growth of GaAs in the corners of the steps, thus yielding arrays of GaAs QWRs embedded in AlGaAs.² Anisotropy in the photoluminescence intensity ratio of the electron-heavy hole to electron-light hole transitions showed evidence for 2D quantum confinement in these QWRs. Semiconductor lasers prepared from such QWR material operated at room temperature, although the effect of the (2D) quantum confinement was not apparent in the lasing characteristics.³

We have developed a novel technique for lateral patterning of QWL heterostructures using epitaxial growth on patterned, nonplanar substrates.⁴ The grown heterostructures exhibit lateral thickness variations, which translate into lateral band gap variations through the strong dependence of the confinement energy on the QWL thickness. Single QWR GaAs/AlGaAs lasers were thus formed by organometallic chemical vapor deposition on V-grooved substrates (see figure). The QWR has a crescent-shaped cross section and is ~ 100 Å thick and less than 1000 Å wide. The tapered QWL at the crescent region gives rise to the lateral potential well, which leads to 2D quantum confinement of the injected carriers. Evidence for this 2D confinement at room temperature was found in the laser spectra, which exhibit enhanced emission at photon energies corresponding to transitions between the QWR subbands.⁵ Threshold currents, already as low as 3.5 mA, are expected to fall to the microampere regime with design optimization.

Fabrication techniques similar to those that are being developed for QWR lasers will lead to the realization of two-dimensional, and eventually three-dimensional, patterned quantum well heterostructures. These novel quantum structures are expected to be useful in a new generation of optical and electronic devices based on quantum interference.

REFERENCES

1. M. Cao, P. Daste, Y. Miyamoto, Y. Miyake, S. Nogiwa, S. Arai, K. Furuya, and Y. Suematsu, *Electron. Lett.* **24**, p. 824, 1988.
2. M. Tsuchiya, J.M. Gaines, R.H. Yan, R.J. Simes, P.O. Holtz, L.A. Coldren, and P.M. Petroff, *Phys. Rev. Lett.* **62**, p. 466, 1989.
3. M. Tsuchiya, P.M. Petroff, and L.A. Coldren, 47th Annual Device Research Conference, paper IVA-1, MIT, Cambridge, Mass., 1989.
4. E. Kapon, M.C. Tamargo, and D.M. Hwang, *Appl. Phys. Lett.* **50**, p. 347, 1987.
5. E. Kapon, D.M. Hwang, and R. Bhat, *Phys. Rev. Lett.* **63**, p. 430, 1989.

Observation of optically pumped intersubband emission from quantum wells

*J.W. Bales, K.A. McIntosh, T.C.L.G. Sollner,
W.D. Goodhue, and E.R. Brown, MIT*

There is growing interest in new devices based on confined states in quantum wells. Optical transitions between subbands are of special interests because they can be tuned over most of the far- and mid-infrared spectrum. Spontaneous emission from transitions between subbands in isolated quantum wells has been observed by Helm et al.¹ by electrically heating the electrons. We describe here the observation of radiative intersubband transitions by optically excited carriers in a quantum-well structure.

In a single quantum well, electrons are localized in one dimension by the atomically abrupt junctions between semiconductor compounds. This confinement is accurately modeled as a rectangular potential well and results in quantization of the kinetic energy in the confined direction. The allowed kinetic energy is continuous in the other two directions, resulting in an energy spectrum consisting of a series of so-called subbands. Each subband has a minimum energy given by the quantized value, which is determined by the well parameters. Within a given subband, the higher energy states correspond to electrons with greater kinetic energy in the unconfined directions.

If two such quantum wells are separated by a thin tunneling barrier, then a coupled quantum well (CQW) is formed (top figure). Our work uses the subband splitting inherent in CQWs. In a symmetric coupled-well system, each subband of the uncoupled well is split into two subbands—a symmetric subband with slightly lower energy and an anti-symmetric subband with slightly higher energy. Intersubband transitions only occur between subbands of opposite parity and only for light polarized with the electric field parallel to the direction of confinement. In the system studied here there are four subbands, labeled E_1 through E_4 in the top figure.

The emission spectrum shown in bottom figure was obtained while the sample was cooled and illuminated with a power of approximately 6 W from a CO₂ laser operated at a wavelength of 9.34 μm (133 meV photon energy), near the peak of the E_1 - E_4 transition. We attribute the 3-meV-wide peak at 17 meV to spontaneous emission by electron transitions from the E_4 subband to the E_3 subband. Calculations indicate that the low energy shoulder at 12.5 meV may be radiation from a region of the sample where the coupling barrier is one monolayer thicker. There is also a sharply rising feature at higher energy that