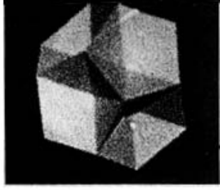


a role to lesser quality films such as amorphous Si and GaAs on Si. For some time now, researchers have sought to avoid that compromise altogether by attempting to create epitaxial quality thin films on arbitrary substrates while simultaneously maintaining the ultimate in crystalline perfection. If such a materials technology were available, it could be expected to play an increasing role in semiconductor and opto-electronics.

The ability to prepare such films leads to a number of interesting possibilities. An obvious one is to combine GaAs optoelectronic and Si integrated-circuit technologies by mounting lifted-off AlGaAs lasers and detectors on Si chips, with the AlGaAs devices providing secure, high-speed interchip communications by optical means. More exotic possibilities, such as mounting GaAs lasers between metal plates to increase thermal dissipation and to reduce noise by suppression of spontaneous modes, can also be envisioned.

One approach is to regard the substrate wafer as a kind of reusable template that can be separated physically from the film after epitaxial growth is completed. The key is to incorporate a release layer in the structure that allows separation to occur. In very early work,[2] Milnes and Feucht proposed that an epitaxial Si film could be separated from an Si substrate by melting an intermediate release layer of Si_xGe_{1-x} alloy. Later the so-called "CLEFT" approach developed by Fan[1] achieved separation by means of a striped carbon film deposited on a semiconductor substrate. Upon cleavage, the film separates in the carbon striped layer that is mechanically weaker than the rest of the crystal.

The natural chemical selectivity among different alloys of the series $Al_xGa_{1-x}As$ suggests a simpler approach. In a little noticed paper almost 10 years ago,[3] Konagai et al. showed that good selectivity could be obtained by etching away a release layer of AlAs in hydrofluoric[4] acid. They did not follow up this work, but further improvements were later achieved at Rockwell and described in an unpublished report.[5]

Recently, Yablonovitch, Gmitter, and co-workers at Bellcore appear to have ironed out the remaining kinks in the process. Large-area (cm square), electronic grade, multilayer GaAs and $Al_xGa_{1-x}As$ ($x \leq 0.4$) single-crystal films already containing fabricated devices are lifted off single-crystal GaAs substrates.[6] The substrates can be reused and the films can be mounted on arbitrary substrates, including Si wafers. As a demonstration, these workers fabricated AlGaAs lasers on glass substrates, with no loss of performance.

To achieve these capabilities, two new insights had to be implemented. First, the selectivity had to be made extremely high. This was accomplished by chilling the acid bath below 0°C. Al-rich AlGaAs alloys etch rapidly and independently of temperature, while Ga-rich AlGaAs alloys etch via a thermally activated process. At 0°C, the selectivity between the AlAs release layer and alloys like $Al_{0.4}Ga_{0.6}As$ reaches $\sim 10^7$.

Second, the gaseous reaction products of the etch had to be removed without creating bubbles that could fracture the thin film. This problem was well known,[1] but the intuitively obvious approach of making the release layer as thick as possible to provide a wide opening for the gas to escape is in fact wrong, as wider release layers merely generate more gas. The key is to make the AlAs layer as thin as possible while controlling the stress in the film by a polymeric support layer so that it curls slightly upward as it lifts off. AlAs under layers as thin as 20Å have been used to obtain cm-square $Al_xGa_{1-x}As$ films.

REFERENCES

1. J.C.C. Fan, J. Physique **43**, C1–327, 1982.
2. A.G. Milnes and D.L. Feucht, in Proc. 11th IEEE Photovoltaic Spec. Conf. (IEEE, N.Y., 1975), p. 338.
3. M. Konagai, M. Sugimoto, and K. Takahashi, J. Cryst. Growth **45**, 277, 1978.
4. A similar process using HCl was described by F. Stern and J.M. Woodall, J. Appl. Phys. **45**, 3904, 1974.
5. D.L. Miller, W.E. Burke, W.I. Simpson, J.J.J. Wang, S.W. Zehr, and J.S. Harris (unpublished, 1982).

I N T E G R A T E D   O P T I C S

COMPACT, LOW-LOSS SEMICONDUCTOR WAVEGUIDE BENDS

R.J. DERI
BELL COMMUNICATIONS RESEARCH
RED BANK, N.J.

Monolithic opto-electronic integrated circuits, integrating active and passive optical and electronic components on a single chip are the subject of active research at numerous laboratories around the world, particularly for potential applications in optical communications systems.

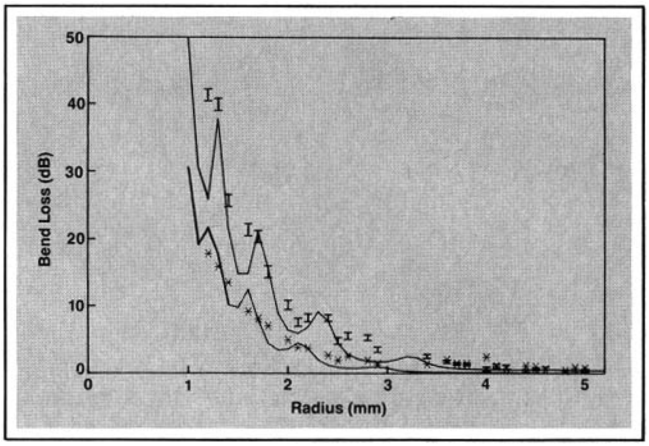
One of the many technical challenges in this field is the fabrication of effective optical waveguide structures using semiconductor materials. In recent years, advances in semiconductor epilayer growth and waveguide fabrication techniques have resulted in straight semiconductor waveguides with low propagation losses (0.15 dB/cm).[1,2] The remaining challenge has been to fabricate low-loss semiconductor waveguide bends, since the minimum usable bend radius has a major influence on the chip size required for a given optical guided-wave circuit, and thus on the ultimate cost per circuit. This year there have been significant advances in the fabrication of compact (approx. 1 mm. radius) bends and in understanding loss mechanisms in such structures.

Waveguides useful for small radius bends must have a tightly-confined optical mode to minimize bend radiation loss, but the techniques used to obtain a confined mode have typically increased scattering losses to unacceptable levels. For example, early work demonstrated guides capable of 300 μm-radius bends, but with propagation (scattering) losses >20 dB/cm.[3]

Recent advances have resulted from improved fabrication techniques, particularly in dry etching, to fabricate deeply etched ribs with smooth surfaces and low scattering loss. Groups at Bell Communications Research[4] and NTT Opto-Electronics Laboratories[5] have reported GaAs/AlGaAs heterostructure waveguides that exhibit low propagation loss and are suitable for compact bends with radii of a few millimeters. Typical performance was an excess bend loss of 1 dB per quarter circle (90° bend) for a 4 mm. radius[4,5] and propagation loss as low as 0.3 dB/cm;[4] bends with a 1 mm. radius for 1 dB/90° bend radiation loss can also be achieved with a modest increase in propagation loss to 1 dB/cm.[4] This low-loss, compact bend technology was recently used to fabricate a guided-wave two-channel wavelength multiplexer on gallium arsenide using an asymmetric Mach-Zehnder interferometer.[6] A more compact device (< 7 mm for 19 nm wavelength channel spacing) was achieved than is possible using earlier reported low-loss semiconductor waveguides (estimated 19 mm device length).

When circular bends and straight waveguides are combined in integrated-optic circuits, interference between guided and radiated light is predicted to result in "coherent coupling" and an oscillatory dependence of bend loss on radius; such behavior would significantly complicate the design of low-loss guided-wave devices. This concern, however, has been alleviated by experiments demonstrating that, for typical rib etch depths, the coherent oscillations are much weaker than predicted by beam propagation simulations,[7] presumably because of scattering effects.

Excepting this loss of contrast, the experimental results are in excellent absolute agreement with the simulations



Bend radiation loss as a function of bend radius and polarization. Experimental results for a 90° circular bend are indicated by error bars (TE polarization) and asterisks (TM polarization) for a single-heterostructure GaAs/AlGaAs rib waveguide.[7] The solid curves (digitized in 0.1 mm radius increments) show theoretical results obtained with the beam propagation method, which employs no adjustable parameters.

(see figure). For waveguides with very tight optical confinement, however, the situation is more complicated because bend radiation propagates into the semiconductor substrate supporting the waveguiding layer, rather than in the plane of the bends as is the case for typical semiconductor guides. Researchers at the University of Sheffield[8] have developed a method for computing bend losses in this limit, which is in close agreement with experiment. Thus, a more complete theoretical understanding of bend radiation loss has emerged.

REFERENCES

1. T.P. Lee, Optics News 13, 37, December 1987.
2. E. Kapon and R. Bhat, Appl. Phys. Lett. 50, 1628, 1987.
3. M.W. Austin and P.G. Flavin, J. Lightwave Technol. LT-1, 236, 1983.
4. R.J. Deri, E. Kapon, and L.M. Schiavone, Electron. Lett. 23, 845, 1987.
5. H. Takeuchi and K. Oe, in *Technical Digest of the 1988 Conference on Integrated and Guided-Wave Optics* (Santa Fe, N. M.; March 1988), Paper MB6.
6. A. Yi-Yan, R.J. Deri, R.J. Hawkins, and M. Seto, to be presented at the 1988 LEOS Annual Meeting (Santa Clara, Calif.; November 1988).
7. R.J. Deri, R.J. Hawkins, E. Kapon, and L.M. Schiavone, in *Technical Digest of the 1988 Conference on Integrated and Guided-Wave Optics* (Santa Fe, N. M.; March 1988), paper MB5.
8. M.S. Stern, P.C. Kendall, and P.N. Robson, Electron. Lett. 24, 17, 1988.