Similar relations with respect to the substrate implant are observed for diodes fabricated by Zn diffusion instead of Be implantation. In addition, Zn-diffused diodes exhibit leakage

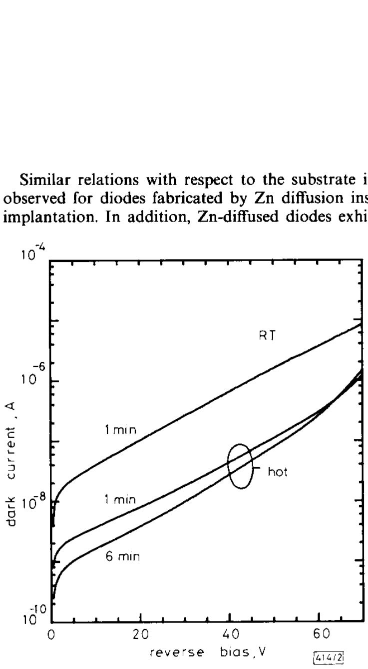

Fig. 2 *Reverse I/V characteristics of planar Be-implanted diodes fabricated in layers grown on Si-implanted InP substrates*

Annealing time and implantation temperature of Si implant are indicated; diode diameter = 50 μm

currents comparable to those of Be-implanted diodes. This is in contrast with the behaviour observed without substrate implant and indicates that good annealing of the substrate implant is much more critical than that of the Be-implanted region.

A strong correlation is observed between the intensity of the room-temperature photoluminescence (RT-PL) of the GaInAs layer and the resulting leakage currents. This is shown in Fig. 3, where the PL intensity measured after epitaxial growth on unimplanted or Si-implanted and annealed substrates is plotted against current measurements on the same samples after diode fabrication. It is clearly seen that the higher the RT-PL-intensity of the GaInAs layer, the lower the leakage currents of the final diodes. Hot substrate implants lead to higher RT-PL intensities than RT implants, indicating that layers of better quality can be grown on substrates with hot implants than on those with RT implants.

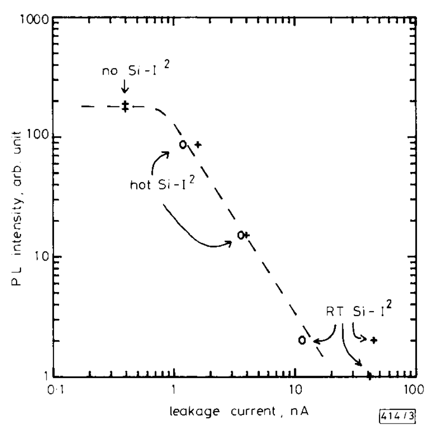

Fig. 3 *Correlation between room-temperature photoluminescence intensity of GaInAs layer before acceptor doping and leakage current (at −10 V) of final diodes (50 μm diameter)*

Influence of substrate implant is clearly seen
+ Be-implanted ○ Zn-diffused

In conclusion, low-leakage GaInAs *pin* diodes using Be implantation and epitaxial growth on Si-implanted InP:Fe have been demonstrated. Both the leakage current and the RT-PL measurements have shown that the proper processing of the substrate implant is the crucial step in diode fabrication.

W. HÄUSSLER *5th July 1989*
D. RÖMER
J. G. BAUER
T. SCHERG

Siemens Research Laboratories
Otto-Hahn-Ring 6, 8000 München 83, Federal Republic of Germany

References

1 AKAHORI, Y., HATA, S., IKEDA, M., YUDA, M., KAWAGUCHI, Y., and UEHARA, S.: 'Monolithic InP/GaInAs *pin*FET receiver using MOMBE-grown crystal', *Electron. Lett.*, 1989, **25**, pp. 37–38
2 ALBRECHT, H., and LAUTERBACH, C.: 'Monolithically integrated InGaAs/InP:Fe photodiode-JFET combination', *Siemens Res. Dev. Rep.*, 1988, **17**, pp. 195–198
3 HÄUSSLER, W., RÖMER, D., and PLIHAL, M.: 'Ion implantation into InP for optoelectronic devices', *Siemens Res. Dev. Rep.*, 1988, **17**, pp. 177–183
4 HÄUSSLER, W., WALTER, J. W., and MÜLLER, J.: 'Ion implantation into InP/InGaAs heterostructures grown by MOVPE'. Paper presented at the Mat. Res. Soc. spring meeting, San Diego, USA, April 1989; to be published in *Mat. Res. Soc. Proc.*

HIGH-REFLECTIVITY $AlAs_{0.52}Sb_{0.48}$/GaInAs(P) DISTRIBUTED BRAGG MIRROR ON InP SUBSTRATE FOR 1·3–1·55 μm WAVELENGTHS

Indexing terms: Semiconductor lasers, Semiconductor devices and materials, Quantum optics

Periodic $AlAs_{0.52}Sb_{0.48}/Ga_{0.47}In_{0.53}As$ quarter-wave distributed Bragg reflectors on InP substrates were prepared and with only eight pairs a peak reflectivity of 90% and a bandwidth of ≥0·2 μm were measured. By the addition of P to the GaInAs alloy, this mirror structure would be useful for InP-based surface emitting laser application at 1·3–1·55 μm wavelengths and would be superior to the previously studied GaInAsP/InP structure, where ~20 pairs are required to achieve similar reflection.

There has been growing interest in vertical cavity surface-emitting lasers,[1–4] stemming from the many advantages that the surface-emitting geometry holds over the edge-emitting geometry. These include the ease of fabrication of integrated laser arrays, wafer-scale testing, self-aligned optical fibre coupling, and chip-to-chip communication via micro-optic components.[5]

For GaAs-based vertical lasers with an active region consisting of GaAs bulk, GaAs/AlGaAs quantum wells, or GaInAs/GaAs strained quantum wells, periodic quarter-wave Bragg reflectors of $Al_xGa_{1-x}As/Al_yGa_{1-y}As$ ($x \sim 0$, $y \sim 1$) were demonstrated as effective reflectors[2–4] owing to the large refractive index difference between the two constituents ($\Delta n \sim 0·6$ for $y - x \sim 1$). At the 1·3 and 1·55 μm wavelength regions presently favoured for optical communication applications, GaInAsP/InP quarter-wave stacks have also been demonstrated on InP substrates.[6–7] However, owing to a small index difference between the $Ga_xIn_{1-x}As_yP_{1-y}$ and the InP ($\Delta n \sim 0·25$ for $x \sim 0·4$),[8] many pairs are required for effective reflectivity. For example, Tai, *et al.*[7] used 20 pairs of InP and $Ga_{0.37}In_{0.63}As_{0.80}P_{0.20}$ with a total thickness of ~5 μm to achieve 92·5% reflection at 1·5 μm. For reflectivities greater than 95% which is necessary for low-threshold surface-emitting lasers, more layers are required. This approach soon becomes impractical in terms of thickness. Furthermore, with such thickness optical loss mechanisms may dominate so that additional reflector pairs will not increase the overall reflectivity. In this letter we investigate another lattice matched combination, $AlAs_{0.52}Sb_{0.48}$/GaInAs(P) on InP substrates for a Bragg reflector.

$AlAs_{0.52}Sb_{0.48}$ has an energy gap at a Γ point of ~ 2.6 eV,* which is much larger than that of InP (1·35 eV). Since the index difference scales with the Γ energy gap difference, a larger index difference can be achieved in the 1·3–1·55 μm wavelengths by the AlAsSb/GaInAsP structure than by the previously studied InP/GaInAsP structure, therefore fewer pairs are needed to achieve the same reflectivity using AlAsSb. Since the width of the Bragg reflection band is linearly proportional to the index difference,[9] a wider reflection band can also be achieved in the AlAsSb/GaInAsP quarter-wave structure.

In the experiments, two samples consisting of six and eight pairs, respectively, of GaInAs (1250 Å nominal thickness) and AlAsSb (1470 Å) were prepared by molecular beam epitaxy on (001) InP substrates. The last layers adjacent to the air were the higher index GaInAs layers. An X-ray diffraction technique was used to check the lattice matching condition.

Fig. 1 shows the measured reflection spectrum for the eight-pair sample. A 90% reflectivity near 1·7 μm is seen with a

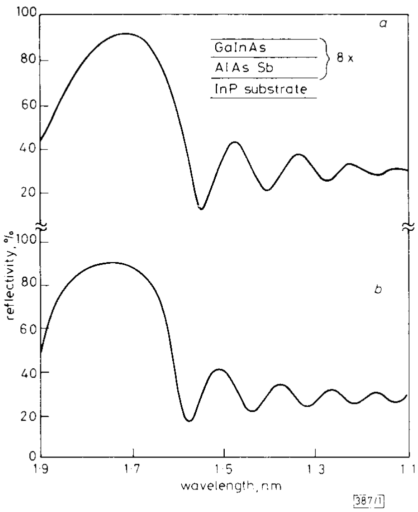

Fig. 1

a Measured mirror reflection spectrum for eight-pair GaInAs/AlAsSb Bragg structure
b Calculated reflection spectrum for structure in (*a*); $\Delta n = 0.5$

reflection band width of 200 nm. A similar spectrum was obtained for the six-pair sample with 83% reflectivity. A numerical calculation was performed assuming the constant refractive indices of 3·5 and 3·0 ($\Delta n = 0.5$) for GaInAs and AlAsSb, respectively. Contributions from the air-GaInAs interface were included in the calculation. The results are shown in Fig. 1*b* with a peak reflection of 0·895; good agreement is found. Since the measured reflectivity is likely to be affected by the quality of the present sample, the index discontinuity in the GaInAs/AlAsSb structure should be greater than 0·5.

For reflectors in the 1·3–1·55 μm wavelengths, optically transparent GaInAsP (e.g. λ_{E_g} (GaInAsP) = 1·2–1·45 μm) instead of GaInAs is used. Numerical calculation for 1·55 μm reflector design using GaInAsP ($E_g \sim 1.45$ μm) shows that 15 pairs will result in 98·7% (96%) reflectivity with (without) an air interface.

We conclude that GaInAsP/AlAsSb Bragg structures have a large index discontinuity to be useful for Bragg reflectors in InP-based 1·3–1·55 μm vertical cavity surface-emitting lasers. The GaInAsP/AlAsSb reflector structure is about half as thick as the previously studied GaInAsP/InP structure for the same reflectivity. The thin structure eases the crystal growth and reduces the cavity diffraction and absorption loss, essential for the performance of a vertical laser.

K. TAI
R. J. FISCHER
A. Y. CHO

AT&T Bell Laboratories
Murray Hill, NJ 07974, USA

K. F. HUANG

Chiao Tung University
Hsinchu, Taiwan, Republic of China

3rd July 1989

References

1 KOYAMA, F., TOMAMATSU, K., and IGA, K.: 'GaAs surface emitting lasers with circular buried heterostructure grown by metalorganic chemical vapor deposition and two-dimensional laser array', *Appl. Phys. Lett.*, 1988, **52**, pp. 528–529
2 SAKAGUCHI, T., KOYAMA, F., and IGA, K.: 'Vertical cavity surface-emitting laser with an AlGaAs/AlAs Bragg reflector', *Electron. Lett.*, 1988, **24**, pp. 928–929
3 ZINKIEWICZ, L. M., ROTH, T. J., MAWST, L. J., TRAN, D., and BOTEZ, D.: 'High power vertical-cavity surface-emitting AlGaAs/GaAs diode lasers', *Appl. Phys. Lett.*, 1989, **20**, pp. 1959–1961
4 FISCHER, R., TAI, K., HUANG, K. F., DEPPE, D., and CHO, A. Y.: 'Extremely low current thresholds in vertical cavity surface emitting laser diodes by use of hybrid mirrors', *Appl. Phys. Lett.*, pending
5 IGA, K., KOKUBUN, Y., and OIKAWA, M.: 'Fundamentals of micro-optics' (Academic Press, Florida, 1984)
6 CHAILERTVANITKUL, A., IGA, K., and MORIKI, K.: 'GaInAsP/InP surface emitting laser ($\lambda = 1.4\mu m$, 77 K) with heteromultilayer Bragg reflector', *Electron. Lett.*, 1985, **21**, pp. 303–304
7 TAI, K., MCCALL, S. L., CHU, S. N. G., and TSANG, W. T.: 'Chemical beam epitaxially grown InP/InGaAsP interference mirror for use near 1·55 μm wavelength', *Appl. Phys. Lett.*, 1987, **51**, pp. 826–827
8 SUEMATSU, Y., IGA, K., and KISHINO, K.: *in* PEARSALL, T. P. (Ed.): 'GaInAsP Alloy Semiconductors', (John Wiley and Sons, NY, 1982)
9 GOURLEY, P. L., BIEFELD, R. M., DRUMMOND, T. J., and ZIPPERIAN, T. E.: 'Epitaxial semiconductor optical interference devices', Proc. of SPIE, 1987, Bay Point, pp. 178–188

* Linear extrapolation of E_g at Γ between AlAs and AlSb is used.

OPTIMUM THRESHOLD SOFT DECISION DECODING OF LINEAR BLOCK CODES IN IMPULSIVE NOISE

Indexing terms: Signal processing, Codes and coding, Noise, Phase-shift keying

The union and upper bounds of the probability of error P_e, for soft decision (unquantised) optimum threshold decoding of binary phase-shift keying (PSK) with the Golay (23, 12) code are found. Even though soft decision decoding performs better, as expected, than hard decision-bounded distance decoding, the difference in performance between the two decoding schemes decreases as the data sample size N becomes large, while the difference between the upper and union bounds remains almost constant. For example, for $P_e \simeq 10^{-5}$ improvement greater than 3 dB can be achieved when going from $N = 100$ to 400. This result is in direct contrast with the equivalent result in white Gaussian noise where a 2 dB difference exists between hard and soft-decision decoding for all coded digital communications.

Introduction: Coding for channels for which the additive noise is not Gaussian is far from understood, and as such it remains an open field of research. For example, the underwater acoustic and radio HF channels are both affected by additive noise and interference which is highly non-Gaussian, these being reverberation and 'broadband' impulsive atmospheric noise, respectively. Both these kinds of noise can be adequately modelled via the recently developed tractable, analytical-physical