References

1 DE LA FUENTE, R., and BARTHELEMY, A.: 'Spatial soliton-induced guiding by cross-phase modulation', *IEEE J. Quantum Electron.*, 1992, **28**, (2), pp. 547–554

2 MORIN, M., DUREE, G., SALAMO, G., and SEGEV, M.: 'Waveguides formed by quasi-steady-state photorefractive spatial solitons', *Opt. Lett.*, 1995, **20**, (20), pp. 2066–2068

3 MAMYSHEV, P.V., VILLENEUVE, A., STEGEMAN, G.I., and AITCHISON, J.S.: 'Steerable optical waveguides formed by bright spatial solitons', *Electron. Lett.*, 1994, **30**, (9), pp. 726–727

4 STEGEMAN, G.I., MAMYSHEV, P., TORRUELLAS, W., VILLENEUVE, A., and AITCHISON, J.S.: 'Photonic applications of spatial soliton switches'. SPIE, 1995, **2481**, pp. 270–278

5 AKHMANOV, S.A., KHOKHLOV, R.V., and SUKHORUKOV, A.P.: 'Self-focusing, self defocusing and self-modulation of laser beams' *in* ARECCHI, F.T., and SCHULZ-DuBOIS, E.O.: 'Laser handbook' (North Holland, Amsterdam, 1972), pp. 1171–1172

6 BJORKHOLM, J.E., and ASHKIN, A.: 'CW self-focusing and self-trapping of light in sodium vapour', *Phys. Rev. Lett.*, 1973, **32**, (4), pp. 129–132

7 LAWRENCE, B., CHA, M., KANG, J.U., TORRUELLAS, W., STEGEMAN, G.I., BAKER, G., METH, J., and ETEMAD, S.: 'Large purely refractive nonlinear index of single crystal p-toluene sulfonate (PTS) at 1600 nm', *Electron. Lett.*, 1994, **30**, (5), pp. 447–448

8 WRIGHT, E.M., LAWRENCE, B.L., TORRUELLAS, W.E., and STEGEMAN, G.I.: 'Stable self-trapping and ring formation in PTS', *Opt. Lett.*, 1995, **20**, (24), pp. 2481–2483

Fabrication of a microengineered quadrupole electrostatic lens

R.R.A. Syms, T.J. Tate, M.M. Ahmad and S. Taylor

Indexing terms: Electrostatic lenses, Micromachining

A self-aligning method of mounting four parallel cylindrical electrode rods in the geometry of a miniature quadrupole electrostatic lens is described. Pairs of electrode rods are mounted in V-grooves, which are fabricated by anisotropic etching of Si wafers. Two etched dies, separated by further insulating cylindrical spacer rods, comprise a complete lens assembly. For prototype lenses with 500μm electrode diameter, electrode spacings were maintained to within 3% of their design value, suggesting that this method of construction will allow sufficient precision for such lenses to act as mass analysers in miniaturised quadrupole mass spectrometers.

An ideal electrostatic quadrupole lens consists of a set of four parallel electrodes with a hyperbolic cross-section, which carry potentials $\pm\phi_0/2$ as shown in Fig. 1*a*. This structure gives rise to a 2D hyperbolic field with a potential variation of the form $\phi(x,y) = \phi_0(x^2-y^2)/2r_0^2$, where r_0 is a characteristic radius. When driven by a time-varying potential $\phi_0 = U-V\cos(2\pi ft)$, this field may provide mass-dependent focusing for ions passing along the centre-line of the lens. If the voltages U and V are scanned, while maintaining a fixed ratio between U and V, a mass spectrum may be obtained from the transmitted ion current [1, 2].

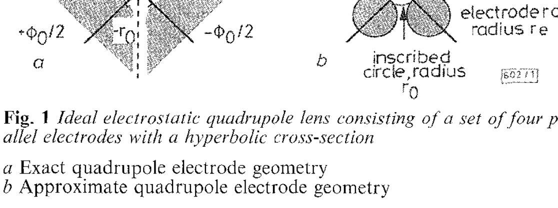

Fig. 1 *Ideal electrostatic quadrupole lens consisting of a set of four parallel electrodes with a hyperbolic cross-section*

a Exact quadrupole electrode geometry
b Approximate quadrupole electrode geometry

A good approximation to the desired electrostatic field is created by an assembly of four parallel cylindrical electrodes of radius r_e, whose centres lie on the corners of a square (Fig. 1*b*). Experimental measurements [3] have long suggested that optimum performance is obtained when r_e is related to the radius r_0 of the inscribed circle separating the rods by the ratio $r_e = 1.148r_0$. For high resolution, a mounting procedure capable of holding the electrodes accurately parallel at this separation is then required [4]. With typical electrode diameters of order 1cm, a common solution is to use ground stainless steel cylinders mounted on precision ceramic spacers.

Mass spectrometers based on quadrupole lenses with cylindrical electrodes are now highly developed and successful. However, the precision assembly is so costly that (for example) economic methods to construct lens arrays have only recently been devised [5]. In addition, the lenses are bulky, delicate and require large drive voltages at RF frequencies. If costs, sizes and voltages can be reduced, and mechanical robustness increased, the range of applications for mass spectrometer systems should increase dramatically.

Size scaling will clearly affect the performance of all the elements (ion source, mass analyser and detector) of such systems. Here, we consider only the effect on the analyser. It can be shown [1, 2], that the mass resolution ΔM (in a.m.u.) of an electrostatic quadrupole lens is

$$\Delta M \simeq 3.854 \times 10^9\ V_z/f^2L^2 \qquad (1)$$

where V_Z is the axial ion energy in eV, and L the electrode length. To minimise ΔM, V_Z should be minimised; however, V_Z cannot be reduced arbitrarily. The alternative is to increase the product fL. To maintain constant resolution as the lens is miniaturised, the operating frequency must therefore increase. Assuming that the smallest allowable $V_Z \simeq 100\ kT$ (say, 2eV), we require $f \simeq 4$MHz for a basic resolution of $\Delta M \simeq 1$ a.m.u. with a length (say) of $L = 2$cm.

Similarly, the maximum mass M_{max} that can be measured (again in a.m.u.) is [1, 2]:

$$M_{max} = 6.92 \times 10^6\ V_{max}/f^2r_0^2 \qquad (2)$$

For a particular V_{max}, M_{max} is determined by the product fr_0. Assuming that the frequency has been scaled as described above, the mass range is therefore unaffected by overall dimensional reduction. For $M_{max} \simeq 100$ a.m.u., we need $V_{max} \simeq 11$V with $f = 4$MHz and (say) $r_0 = 217.5$μm, corresponding to an electrode diameter of 500μm.

These data suggest that modest performance suitable for a restricted range of applications (but not for precise analysis) can be achieved from a small quadrupole driven with a relatively low voltage at a moderate RF frequency, which could be derived from a simple signal generator. However, assembly methods of the type described earlier would be inappropriate, in terms of both accuracy and cost. Here, we describe a microengineering approach [6], based on a novel application of anisotropic etching techniques previously devised for optical fibre connectors [7].

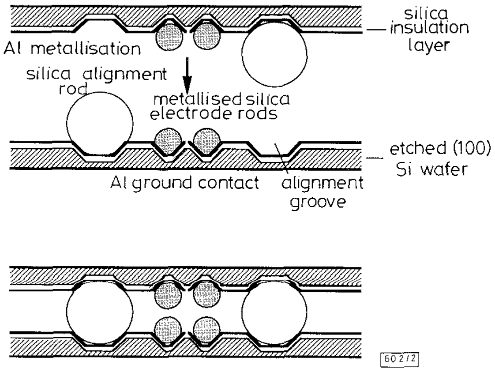

Fig. 2 *Self-aligning microengineered quadrupole lens assembly*

In our microengineered quadrupole, the electrodes are formed from metallised silica rods. These are mounted in pairs on two silicon substrates, which are held apart by additional insulating cylindrical rods as shown in Fig. 2. The correct electrode spacing and alignment are achieved through the use of V-shaped grooves as kinematic mounts for both types of rod. Each Si substrate carries only one alignment rod, which mates with a groove on the other substrate to eliminate all degrees of freedom except axial motion. Provided that tangent plane contacts are made between the rods and the groove walls, this method of construction makes the electrode separation highly immune to variations in groove width. The grooves are formed by anisotropic etching of 3in (100) oriented *p*-type silicon in ethylene diamine pyrocatechol (EDP). After etching, the substrate is electrically isolatedby a 1µm thick layer of thermally-grown silica. Electrode contacts are defined by shadow-masked evaporation of Al metal. Windows are opened in the rear-side oxide layer, and a further Al layer is deposited as a ground connection.

The electrodes are formed from commercial silica rods of 500µm diameter coated with 1000Å Cr metal, mounted so that the surface of the substrate passes through the electrode centre-line. The proximity of a grounded, etched substrate will undoubtedly affect the equipotentials; for example, the presence of a cylindrical shroud around a conventional quadrupole is well-known to alter the optimum electrode spacing [8]. However, for simplicity, this aspect was ignored in the prototype design, and the conventional separation adopted. Some freedom was available in the choice of alignment rod, and a diameter of 1150µm was chosen to minimise the maximum groove depth required. With appropriate clearances, these dimensions allowed sufficient mechanical strength to be retained after etching using an initial wafer thickness of 400µm. The rods were bonded to the substrate under pressure at 180°C using indium as an adhesive.

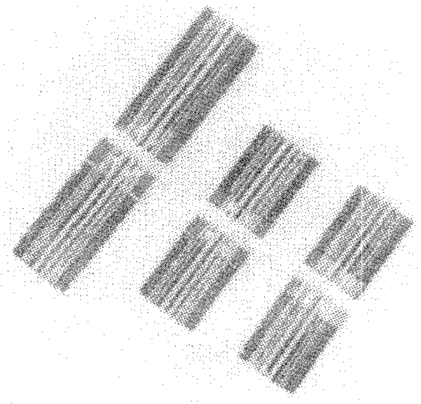

Fig. 3 *Completed half-lens dies, before assembly of full lens unit*

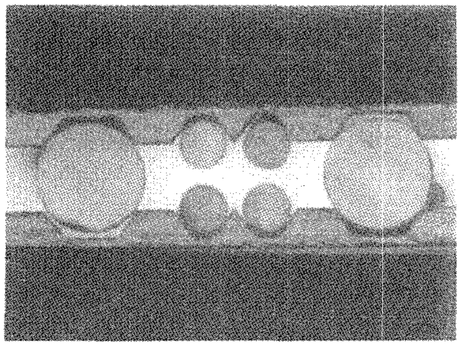

Fig. 4 *End-on optical microscope view of assembled microengineered quadrupole lens*

Each wafer contains features to allow the construction of eight lenses of varying lengths up to 3cm, and yields of ~75% are routinely achieved. Fig. 3 shows half-lens dies of 1 and 1.5cm length after fabrication, and Fig. 4 shows an end-on view of an assembled lens. Tolerances obtained with initial prototypes have been estimated as 1–3%, and are currently limited mainly by failure to seat the rods fully during bonding. The electrostatic performance of the lenses is now under investigation, and these results will be reported elsewhere.

Acknowledgments: The authors are extremely grateful to the EPSRC for financial support of this project through Grant GR1K55868, and to H.A. Dorey and J.H. Leck for their encouragement.

17 September 1996
Electronics Letters Online No: 19961362

R.R.A. Syms, T.J. Tate and M.M. Ahmad (*Optical and Semiconductor Devices Section, Department of Electrical and Electronic Engineering, Imperial College, Exhibition Road, London SW7 2BT, United Kingdom*)

S. Taylor (*Department of Electrical Engineering and Electronics, Liverpool University, Brownlow Hill, Liverpool L69 3BX, United Kingdom*)

References

1 DAWSON, P.H.: 'Quadrupole mass spectrometry and its applications' (Elsevier Scientific Publishing Co., Amsterdam, 1976)
2 BATEY, J.H.: 'Quadrupole gas analysers (residual gas analysis)', *Vacuum*, 1987, **37**, (8–9), pp. 659–668
3 DAYTON, I.E., SHOEMAKER, F.C., and MOZLEY, R.F.: 'The measurement of two-dimensional fields. Part II: Study of a quadrupole magnet', *Rev. Sci. Instrum.*, 1954, **25**, pp. 485–489
4 AUSTIN, W.E., HOLME, A.E., and LECK, J.H.: 'The mass filter: Design and performance' (Chap. 10 in 'Quadruple mass spectrometry and its applications, Elsevier, Amsterdam, 1976, pp. 121–152)
5 FERRAN, J.: 'Residual gas analyser utilizing a miniature quadrupole array'. US Patent 5,401,962, 28 March, 1995
6 TAYLOR, S., SYMS, R.R.A., DOREY, H.A., and TATE, T.J.: 'Improvements in and relating to quadrupole mass spectrometers'. British Patent 9506972.0, 1995
7 SCHROEDER, C.M.: 'Accurate silicon spacer chips for an optical fiber cable connector', *Bell. Syst. Tech. J.*, 1977, **57**, (1), pp. 91–97
8 DENISON, D.R.: 'Operating parameters of a quadrupole in a grounded cylindrical housing', *J. Vac. Sci. Tech.*, 1971, **8**, pp. 266–269

High-breakdown voltage $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/In_{0.75}Ga_{0.25}As/InP$ heterostructure field-effect transistors

Jan-Shing Su, Wei-Chou Hsu, Dong-Tsuen Lin, Wei Lin, Hung-Pin Shiao, Yu-Shyan Lin, Jean-Zen Huang and Piin-Jye Chou

Indexing term: Field effect transistors

$Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}/In_{0.75}Ga_{0.25}As/InP$ heterostructure field-effect transistors (HFETs) with high breakdown voltage have been successfully fabricated by low-pressure metal organic chemical vapour deposition (LP-MOCVD). By virtue of an $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}$ Schottky layer and an inverted δ-doped carrier supplier, a gate-to-drain breakdown voltage as high as 40V can be obtained. Moreover, the temperature dependence of breakdown voltage shows a negative temperature coefficient.

Introduction: InP-based heterostructures have attracted much interest for photonics and microwave power applications. The gate-to-drain breakdown characteristic is the major drawback limiting the power handing capability of heterostructure FETs. Moreover, the dark current reduces the response of MSM photodetectors due to the low Schottky barrier height of InP and InGaAs (below 0.5eV for InP and 0.3eV for InGaAs). Some materials for replacing the InP Schottky layer to enhance the breakdown voltage in InP-based structures have been reported, including InAlAs, which is lattice-matched to InP [1], and AlInAs ($x > 0.48$) [2], $Al_{0.25}In_{0.75}P$ [3, 4], $In_{0.52}Al_{0.48}As_xP_{1-x}$ [5], $Al_{0.1}In_{0.1}Ga_{0.8}P$ [6] and $In_{0.82}Ga_{0.18}P$ strain layers [7], which are lattice mismatched to InP. It is possible to increase the bandgap of the Schottky layer and to improve the gate-to-drain breakdown voltage of HFETs by using a strained layer. However, the reported gate-to-drain breakdown voltages are seldom larger than 30V. Typical breakdown voltage is 10–20V in the strained InP-based HFETs. In this work, we adopted an $Al_{0.66}In_{0.34}As_{0.85}Sb_{0.15}$ Schottky