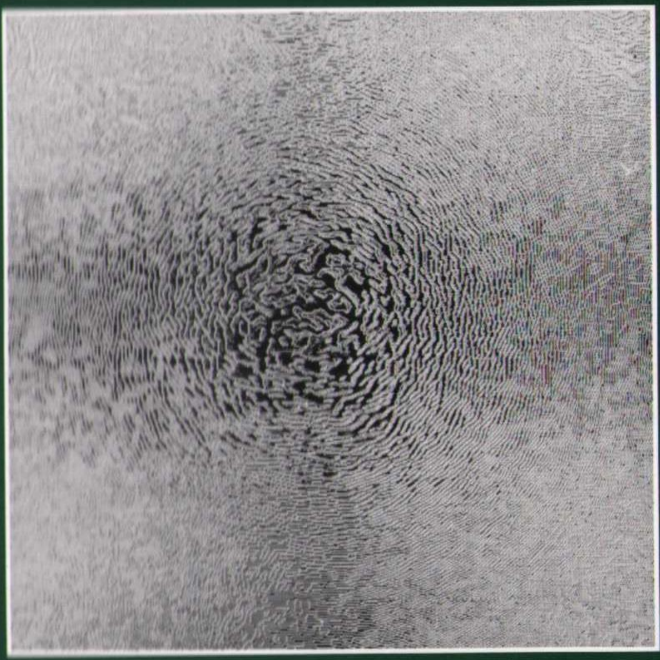
Rutherford Appleton Laboratory

Central Microstructure Facility 1997/8



CLRC
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CMF Management

Professor R A Lawes FEng
Head of the
Central Microstructure Facility

Dr B D Jones
Business Manager

Interface with university and industry users; information on CMF facilities; CAD data processing; job scheduling; contracts, administration and finance.

Professor P D Prewett
Group Leader, R&D

R&D to provide new and improved facilities and services; participation in UK and European collaborative R&D projects.

Mr A W Eastwood
Group Leader,
Microfabrication

Microfabrication services; clean room operation, engineering and maintenance.

Brochure

A brochure specifying CMF equipment and processes is available. It may also be viewed on the **World-Wide Web at http://www.ebl.rl.ac.uk/brochure.html**

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Central Microstructure Facility

1997/98

This is the 1997/98 Annual Report for the Central Microstructure Facility (CMF) at the Rutherford Appleton Laboratory. I am pleased to present this account of the activities at the CMF with and on behalf of UK university and industrial customers and collaborators.

While the core activity of the CMF remains the provision of microstructures for EPSRC grantholders, the CMF continues to develop a portfolio of relevant R&D projects and to help UK industry.

The presence of industry at the CMF continues to grow. Five companies now have formal contracts to research and develop microelectronic and/or microsystems technology, with provision for prototyping as well as routine manufacture when appropriate. In addition, the amount of ad hoc commercial work is increasing steadily.

The role of the CMF as a UK Centre of Excellence for Microtechnology is also recognised through the management of important projects on behalf of the European Commission, for example an increased role in Europractice, involving ASICs, MCMs and MST. The establishment of the Joint Research Laboratory with the Korean Institute of Technology was an important event, one which will add to the international reputation of both parties.

Overall, development of the CMF has been most satisfactory both in the UK and abroad. Highlights of the work of the CMF during 1997/98 are included in this report. I would welcome comments and would be pleased to provide further details on any topic.

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Cover picture: A reflective kinoform made by CMF, designed to reconstruct a Gaussian-shaped CO_2 *laser beam into a rectangle (Section 2.1).*

1. Introduction

In 1997/98 the direct involvement of industry at the CMF grew significantly. Two start-up SMEs came to the CMF to develop flat-panel display technology. Ceravision will exploit the silicon field emission technology developed at the CMF and embed it in their own ceramic tile display developments. PFE will develop a unique large area, low cost field emission technology and use the advanced microtechnology facilities of the CMF to develop new prototypes.

In addition, three companies already at the CMF continued to develop their activities.

Exitech is a local laser technology company with long associations with RAL and the CMF. At present, Exitech and the CMF are working together on laser micromachining and laser cleaning processes.

Qudos has consolidated its customer base and is growing at a steady pace. All their R&D and manufacturing is done at the CMF. For example, the last year has seen both routine production work for their CMOS camera contract and the development of microlenses for various projects and customers.

Bookham has enjoyed considerable success, doubling their staff since last year and developing their position in the market. After several years of tremendous growth, Bookham have moved to a nearby Science Park for the majority of their production and development work, but still retain use of the CMF for R&D.

A notable event during 1997 was the signing of a 3-year agreement to research and develop new microsystems technology between the Korean Institute of Science and Technology (KIST) and CCLRC. The agreement sets up a Joint Research Laboratory within the CMF, allows Korean scientists access to its facilities and will promote the joint development and exploitation of microtechnology.

The R&D programme at the CMF, funded by the Research Councils and the European Commission, continues to provide most of the new technology available to customers and collaborators. In particular, NANCAR and OPTIMA (both EU-funded) are supplying respectively, sub 100 nm ebeam resist technology and sub 0.25 μm optical mask resolution through optical proximity correction. MICROSYNC is another important project bringing together LIGA using X-ray synchrotron radiation and excimer laser micromachining, as applied to high aspect ratio microstructures.

The CMF is being involved increasingly in the overall management of EU programmes in microelectronics and microsystem technology, eg the Semiconductor Equipment Assessment exercise and Europractice. In late 1997, the CMF took responsibility for the Europractice Coordination Office to work with 4 external consultants to oversee the ASIC, multichip modules and Microsystems Technology (MEMS) programmes. In addition, the CMF was appointed as the lead partner for an application based Centre of Competence for 'Process control, machine tool manufacturing, micro-actuators and micromachines' and an associate partner in the Italian Centre of Competence in 'Microfluidic Systems'.

The EPSRC contract to provide microelectronic and microsystems technology to the UK academic community remains the largest single activity at the CMF. Fig 1.1 shows the trend in CMF usage for both electron beam lithography and microengineering. It can be seen that the overall workload at the CMF, arising from the award of EPSRC grants to university researchers, has grown steadily during the last few years with a mix of advanced electron beam lithography and general microengineering. The 'misc' category contains a growing element of purely commercial work, using excess capacity at the CMF to help UK industry.

Publications by CMF users, staff and collaborators are listed in Appendices II and III. The Technical Editor gratefully acknowledges contributions from CMF's academic and industrial contacts.

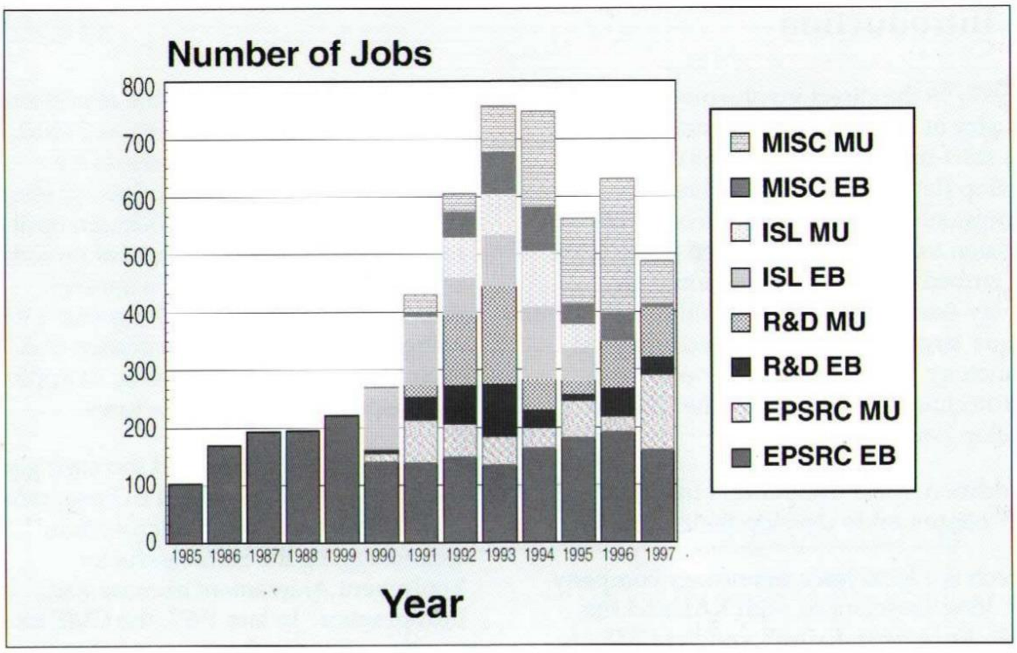
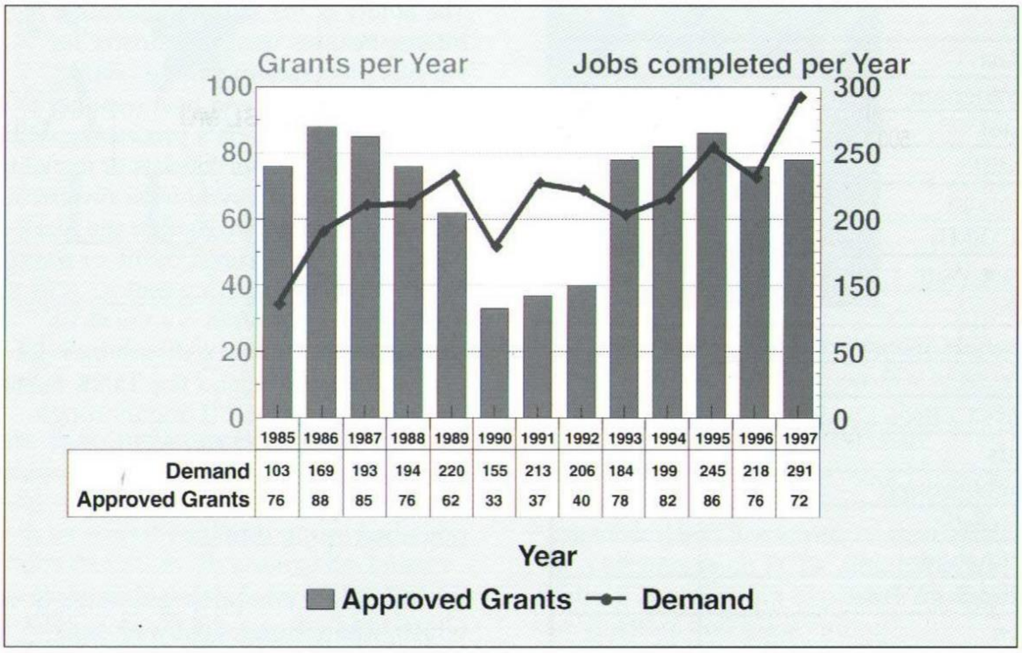


Fig 1.1 Jobs completed at the CMF over the period 1985-98. Jobs were carried out for EPSRC grantholders, as part of R&D programmes funded by EPSRC and the EC and by a variety of other users (Misc) including commercial work. Jobs are further subdivided into those using the electron beam (EB) machines and those using the other microengineering (MU) facilities.

2. EPSRC Programmes and Collaborations



Year	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Demand	103	169	193	194	220	155	213	206	184	199	245	218	291
Approved Grants	76	88	85	76	62	33	37	40	78	82	86	76	72

Fig 2.1 EPSRC grants and CASE studentships over the period 1985-98 involving the use of the CMF, showing the corresponding demand for CMF services in terms of completed jobs

Fig 2.1 shows the average number of EPSRC grants and CASE studentships requiring the CMF during the period 1985-98. The number of jobs completed on behalf of the EPSRC-funded academic community, relative to the number of grants awarded, seems to have increased but this may be a one-off fluctuation.

During 1997-98, 33 universities used the CMF, compared with 30 in 1996-97, led by Nottingham and Imperial. The full list of universities using the CMF in 1997-98 is shown in Table 2.1. University publications arising from their research and supported by the CMF are listed in Appendix II.

An important development is the preliminary 'pump-priming' work being undertaken for university groups preparing more complex EPSRC grant propossals. Flexibility at the CMF enables critical concepts to be tested to ensure a better quality proposal.

As in previous Annual reports, only a few examples of the diverse work undertaken by the CMF can be included. This year, the work highlighted involves Kinoforms for Laser Beam shaping at Loughborough, Microsystems at Imperial College, Multiple Quantum Well Structures at UCL and Integrated Optics at Oxford.

UNIVERSITY	GRANTS
Aberdeen	1
Bangor	2
Bath	4
Belfast	1
Birmingham	1
Bristol	1
Cardiff	3
Cranfield	1
CRL (EMI)	1
Heriot-Watt	2
Hull	1
Imperial College London	7
Kent	1
King's College London	5
Leeds	2
Loughborough	1
Newcastle	1
Nottingham	8
Nottingham Trent	2
Open	1
Oxford	4
Paisley	1
Plymouth	3
RAL	4
Royal Holloway & Bedford	1
Sheffield	2
Southampton	1
Strathclyde	1
Surrey	1
UMIST	3
University College London	4
Warwick	1
York	1
TOTAL OF GRANTS	72
	PRE-GRANT
Birmingham	1
Bristol	1
Cardiff	1
King's College London	1
Open	1
Oxford Brookes	1
University College London	1
TOTAL PUMP PRIMING	8
TOTAL	80

Table 2.1 EPSRC Grants requiring use of CMF, current in 1997/8 plus pump-priming support

2.1 Kinoform Optics for Laser Materials Processing

The ability of the laser to produce a highly intense beam is used in industry for various processes including cutting, welding, marking and heat treatment. Conventional materials processing with high-powered lasers consists of focusing a beam to produce a symmetrically circular spot, and then moving either the workpiece under the focused beam, or the spot itself with beam-steering optics. A focused spot, however, is often not the most appropriate or efficient distribution for practical purposes, and the 'LINK Surface Engineering' project (Loughborough University, TWI and five industrial members) aims to demonstrate the use of kinoform optics in a wide range of industrial applications.

Kinoforms are computer generated devices which, when illuminated with laser radiation, can reconstruct two- and three-dimensional digitally defined images. A kinoform optic consists of a quantised phase pattern transferred into a multilevel surface relief, and the intensity distributions it produces can be uniquely tailored to take into account the material parameters, component geometry and the laser process being used. Fig 2.1.1 shows a kinoform pattern designed to re-shape a circular CO_2 laser beam into the complex pattern in Fig 2.1.2.

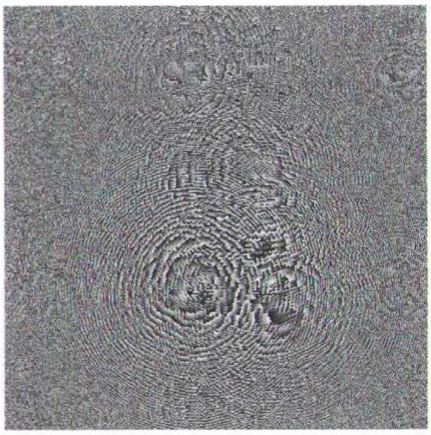


Fig 2.1.1 Kinoform phase pattern quantised to 32 levels: actual size is 35 x 35 mm

Fig 2.1.2 Required image to be reconstructed from kinoform

For use as industrial machine tools, the reconstructed images must be highly efficient with little noise, and this depends on both computational techniques and very accurate fabrication. To achieve the latter, a process for producing kinoforms by direct write electron beam lithography has been developed by the CMF. The pattern in Fig 2.1.1 consists of 512^2 cells in PMGI photoresist with a maximum depth of 5.337 µm, and the 32 quantised depth levels are obtained by multiple doses in an electron beam microfabricator. This process needs extremely careful control, involving multi-dose test runs and accurate depth measurements with a profilometer. The resulting 'dose *vs* depth' curve is then used to give doses for depths of 0, 0.172, 0.344, ... to 5.337 µm. The e-beam exposure parameters are chosen so that the microfabricator grid fits that of the kinoform and the total run time is reasonably short.

After development and gold-coating, the kinoforms are tested in a 2kW CO_2 laser system and have reproduced very accurate images with diffraction efficiencies of up to 92%. Fig 2.1.3 shows a perspex beam print of a reconstructed image, generated by reflecting a 500W collimated CO_2 laser beam with the kinoform in Fig 2.1.1.

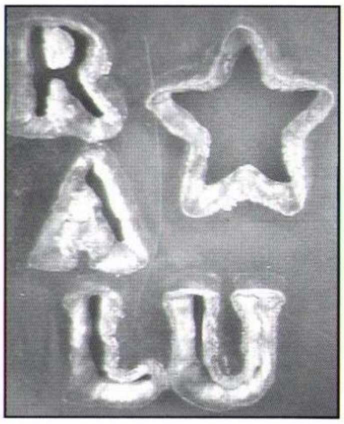


Fig 2.1.3 Photograph of a laser burn print in perspex from above kinoform, size 11 x 14 mm

Kinoform optics have been used successfully at Loughborough University for a variety of applications including transformation hardening of steel; soldering of components on PCBs; simultaneous cutting and welding of plastics for bag production, and glass cutting.

2.2 Microsystems Technology at Imperial College

Work on Microsystems Technology commenced at Imperial College in 1992. Initial collaboration was supported by the appointment of a CASE student and a Research Fellow by CMF, whose Division Head is also a Visiting Professor. Excellent links have been maintained ever since, and a considerable growth in activity has resulted in a number of achievements, some of which are featured below.

A method of fabricating silicon microactuators by bulk micromachining has been devised, where only single-crystal material is used and isolation is provided by diodes. The devices are large compared with surface-micromachined components (several mm span, suspended 100 µm above the substrate), and have large motions. Electrothermal tuning of mechanical resonances has been demonstrated, and a coupled-resonator gyroscope with active frequency-matching is being developed.

Different chemical routes have been investigated for the fabrication of piezoelectric ceramics, for use as actuating layers on silicon microstructures. An alternative to the sol-gel process has been found, based on metal-organic decomposition. This allows rapid production of thick PZT films with good ferroelectrical properties, and bimorph cantilevers based on this material are now being fabricated.

Low-cost alternatives to LIGA processing have been developed. Deep metal microstructures are built up by repeated use of deposition of a conducting seed layer, deposition of photoresist, lithography, and metal electroforming. By combining UV lithography with excimer laser micromachining, complex devices such as a six-level nickel microturbine have been fabricated. A parallel assembly process has also been developed, in which electroformed components are detached from a transparent carrier by ablating an intermediate polymer. Transfer of components from one wafer to mate with components on another is then achieved by bringing the wafers together, aligning them, and exposing the carrier.

A different method of 3D microstructure assembly has been demonstrated, based on out-of-plane rotation and fixing of flat parts. Rotation is powered by the surface tension of pads of meltable material linking each movable part to the substrate. Rotation through a fixed angle (say, 90°) may be achieved by using a simple mechanical limiter, and applications of self-assembly are now being investigated.

Anisotropic etching of (100) Si substrates has been used to fabricate an alignment assembly for cylindrical electrodes in the geometry of an electrostatic quadrupole. This lens is now being used as the mass analyser in a miniaturised mass spectrometer in a collaboration with Liverpool University. Mass filtering has been demonstrated, and resolution and sensitivity are improving rapidly.

Fig 2.2.1 shows a comb drive electrode structure, while Fig 2.2.2 illustrates a wobble motor made of electroplated nickel with a rotor diameter of 1 mm.

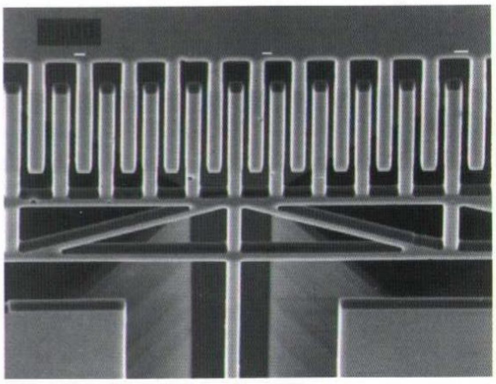


Fig 2.2.1 Comb drive electrode structure of bulk micromachined electrostatic actuator

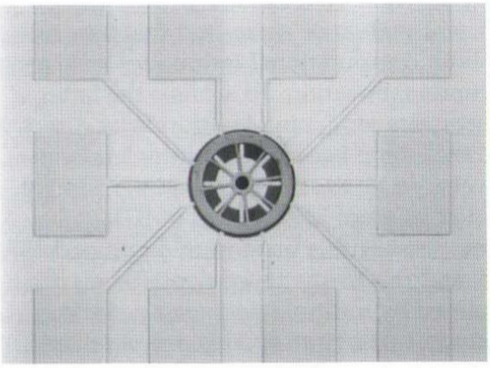


Fig 2.2.2 Wobble motor based on a rotor and stator fabricated on separate substrates and brought together by laser-assisted assembly.

2.3 Multiple Quantum Well Structures in Laser Tuning

Tunable semiconductor lasers with uniform frequency modulation (FM) response are key components in microwave opto-electronic and optical communication systems. Conventional tunable semiconductor lasers employ current injection to achieve tuning by the carrier induced effect (CIE). Whilst this is a convenient method, it suffers from the intrinsic limitation that thermal tuning mechanisms which are dominant at low modulation frequencies (<10 MHz) have the opposite sign from plasma and band filling tuning mechanisms which predominate at higher frequencies, leading to a highly non-uniform FM response. In contrast, an intrinsically uniform FM response can be obtained by using the electro-optic effect in the tuning section, as this effect involves no carriers, thereby eliminating thermal effects. However, the electro-optic effect in bulk semiconductor materials gives a small index change relative to CIE.

The quantum confined Stark effect (QCSE) in a multiple quantum well (MQW) structure provides a comparable refractive index change to CIE, even for wavelength detunings of 10 - 40 nm to the red side of the *e1-hh1* exciton absorption peak. Field effects in significantly reverse biased MQW structures can offer response times in the picosecond region.

In earlier work, a team at University College, London, demonstrated for the first time the use of QCSE as a semiconductor laser tuning method, using an external cavity configuration, and in the current project they are developing a QCSE tuned monolithically integrated two-section MQW ridge guide laser. Being fabricated on a semi-insulating GaAs substrate with post-epitaxy band gap de-tuning and low parasitic capacitance air-bridged contacts, it has simple fabrication requirements and is suitable for application where a uniform FM response over a limited tuning range is required.

Fig 2.3.1 shows the schematic structure of the QCSE tuned laser, which has a threshold current of ~40 mA and a uniform FM response within ±3 dB over the modulation frequency range 30 kHz to 6 Ghz. The seventeen layers in the MQW have thicknesses in the range 6 nm to 3 µm and consist of p-, i- and n-doped GaAs and AlGaAs (Al = 0.45).

Fig 2.3.2 is an SEM picture of the fabricated two-section air-bridged laser.

This project, in the Electronic and Electrical Engineering Department at UCL, relies heavily on multi-institutional collaboration. The epitaxial wafers used for the work are supplied by the EPSRC III-V Semiconductor Facility at Sheffield University, ion implantation and rapid thermal processing is carried out at the EPSRC Ion Beam Facility at the University of Surrey and all the masks used for laser fabrication are made by the CMF. The work is supported by the US AFOSR as well as by EPSRC.

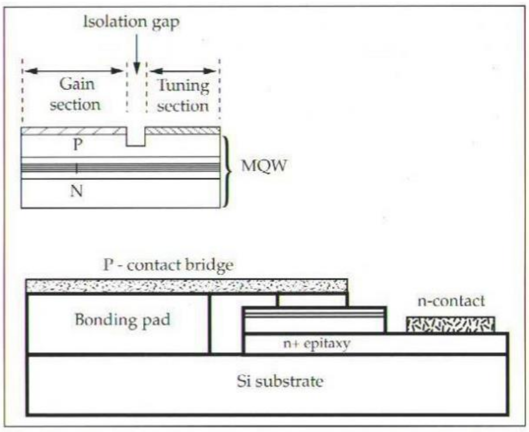


Fig 2.3.1 Cross-sectional views of QCSE tuned laser.

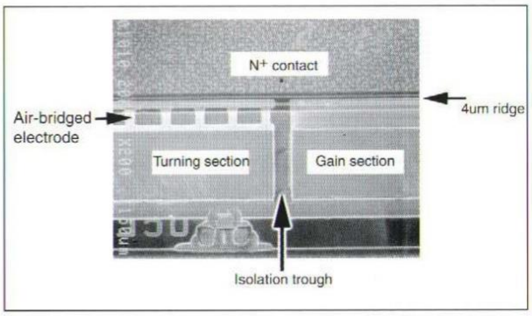


Fig 2.3.2 Annotated SEM micrograph of air-bridged two-section QCSE tuned laser source.

2.4 Integrated Optics at Oxford University

Close links with the CMF over a number of years have continued to assist in the manufacture of complex diffractive optical elements with the use of direct-write electron beam lithography. Research into integrated optical systems at Oxford University has concentrated on the use of grating structures for light coupling and sensor applications, as in the EPRSC projects SOPHI and IOTIS.

For example, coupling laser radiation directly into an optical waveguide, whilst maintaining high efficiency, requires the manufacture of specially shaped gratings. These gratings are typically of submicron pitch and have a smooth variation in both curvature and pitch (i.e. chirp) in order to obtain optimum phase matching between the laser radiation and the optical mode structure of the waveguide. This principle is illustrated in Fig 2.4.1, which shows how the shape of the grating is optimised to couple the waveguide light to a focal point at the photodetector.

Such non-uniform gratings have been written using a combination of direct-write electron beam lithography at the CMF, followed by reactive ion beam milling at Oxford. The milling process is required to etch blazed gratings into the surface of the waveguide, dramatically improving its coupling efficiency.

In addition to laser coupling, the ability to out-couple light propagating along a waveguide has been demonstrated. In this case the etched gratings can form a diffractive optical element to focus the out-coupled light to a remote point a few millimetres above the waveguide surface. Manufactured output couplers have shown close to 90% coupling efficiency, for coupling light from the waveguide into a single focused point. Such components will have applications in optical interconnect schemes, where photodetectors and optical waveguides are integrated on to a single substrate.

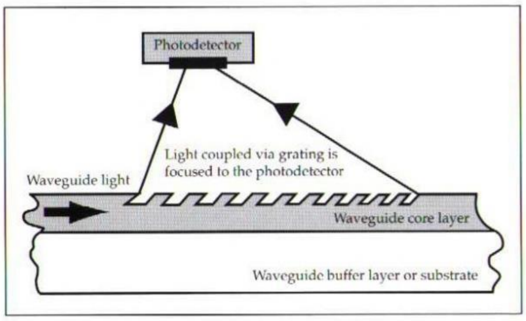


Fig 2.4.1 Blazed grating, with chirp, etched into the surface of the waveguiding layer

3. Process Technology

3.1 EPSRC Customer Support

Mask Making. The support of users funded under the Service Level Agreement (SLA) with the EPSRC falls into various categories, depending on the users' needs and experience. Most SLA work is straightforward mask making through a well-established route, where CAD data are sent to CMF and masks returned. Problems with users' data may need to be sorted out before production - especially with new users - and such interactions have always been a feature of CMF.

CAD Data Processing. Although most customers employ standard integrated circuit design packages, an increasing number use general PC-based packages such as AUTOCAD. These offer a rich variety of data types and file formats, some of which are unsuitable for microfabricators which write shapes as simple trapezoids. Some effort, therefore, was spent in defining which data types are acceptable and in modifying the DXF-format data conversion software. Two particular jobs, for Durham University and UCL, are examples where the lithography was fairly straightforward, but transferring appropriate CAD data needed very close customer liaison.

New Processes. Close user interaction also occurs where partially-processed substrates are exposed at CMF. A typical example is a new thin-film PMMA process for an indium phosphide (InP) substrate for the University of Oxford. Here, a central 2 µm pillar must be surrounded by a set of concentric rings etched into the substrate. The rings, with line widths of 120 and 240 nm, require a basic machine resolution of 20 nm and exposure at 50 kV in the EBML300 microfabricator. Fig 3.1.1 shows features in PMMA on InP from a process test run. Continual process development is a necessary part of user support.

Customer Usage. Some customers visit the Facility to do their own processing: a team from Nottingham Trent University, for example, has used sputtering, plasma enhanced CVD, RIE and argon ion beam milling on a variety of materials - ZnS:Mn, Y_2O_3, Si_3N_4, etc - to increase the efficiency of LETFEL (lateral emission thin film electroluminescent) displays. Fig 3.1.2 shows a demonstration display produced by the Nottingham team. This technology has potential applications as 'head-up' and head-mounted displays (cf Section 6.5).

Training. This use of some CMF apparatus by grant-holders is a constant activity, requiring both training and supervision by CMF staff. It was extended recently when three postgraduates from Birmingham University attended a formal microfabrication course as part of their PhD training. This was instructive for both tutors and students, and demonstrates the role of training in CMF user support.

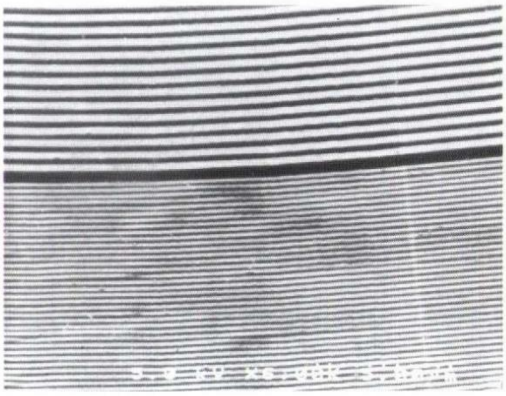


Fig 3.1.1 Concentric rings of PMMA with linewidths of 120 and 240 nm on an indium phosphide substrate

Fig 3.1.2 An example of a 'LETFEL' display from Nottingham Trent University

3.2 Optical Lithography Simulation

CMF and Mitel Semiconductor Ltd (formerly GEC Plessey Semiconductors Ltd) have continued to collaborate closely on optical lithography and its simulation. During the course of this year, and as a result of this close collaboration, they were joined by Align-Rite Ltd in some of their investigations. Some of the topics investigated include:

- process control for sub half micron CMOS technology;
- analysing the dissolution characteristics of G- and I-line diazonaphthoquinone-based photoresists;
- analysing the dissolution characteristics of deep UV chemically amplified photoresist;
- new development models for lithography simulation;
- the influence of lens aberrations on high resolution optical lithography;
- assessment of commercially available software packages for Optical Proximity Correction and its application to full-chip designs;
- investigating the suitability of phase-shifting mask technology to specific commercial applications.

As a result of the work on dissolution characteristics and development models, the PROLITH family of lithography simulation tools now includes a new model developed at CMF, called the 'Notch Model'. This shows significantly improved correlation between simulated and experimental results, and after fine-tuning of the development parameters, allows an extremely wide range of exposure, focus and development time values to be accurately modelled.

Fig 3.2.1 shows how the Notch model compares with two others (Original and Enhanced Mack) when fitted to experimental data. It clearly agrees better with the data, particularly in the critical region of $0.5 < m < 0.6$ which defines the profile of the developed resist.

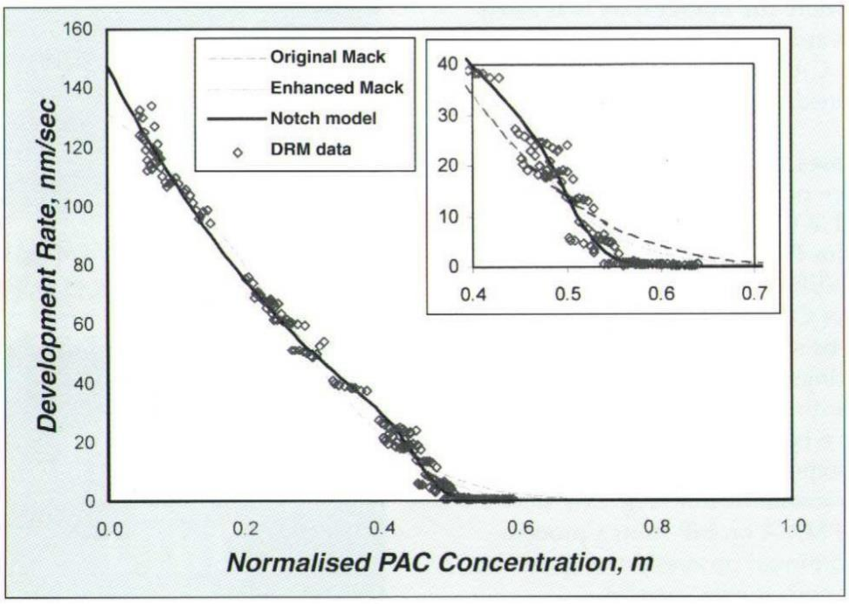


Fig 3.2.1 Comparison of three simulation models with practical data showing the improved accuracy of the Notch Model

3.3 ASNR Resist Process Optimisation

A resist research programme at the University of Kent, in collaboration with GMMT (Caswell) and CMF, has led to the development of a new Application Specific Negative - working Resist ('ASNR'). This is chemically similar to the Japanese CMS resists that were recently withdrawn from the world market. This withdrawal added impetus to work on the new resist, leading to experimental characterisation by a number of academic and industrial e-beam users in the UK. The conclusion of this work, by the Leica Ebeam Users Resist Working Party, was the need for a short programme of ASNR process optimisation, to be carried out at CMF.

During the past year, therefore, CMF has collaborated with Kent to assess various ASNR resists with different sensitivities and polymerisation methods, comparing their lithographic performance and dry etch behaviour with commercial CMS resists. The aim of this work was to optimise the processing procedures for ASNR using carefully designed Taguchi experiments.

Each stage of the process was investigated, from resist spinning, via exposure, development and baking to dry etching. For example, six developer-rinse combinations were investigated, using a variety of solvent combinations which included MIBK (methyl isobutyl ketone), IPA (isopropyl alcohol), IAA (isoamyl acetate), DNBE (di-n-butyl ether), NBA (n-butyl acetate), and HA (hexyl acetate). The lithographic performance was judged in terms of:

- sensitivity
- contrast
- resolution
- edge acuity
- linewidth deviation from nominal

with each of these results being suitably quantified for Taguchi analysis.

The analysis led to a set of process parameters which gave a suitably wide 'process window', where marginal parameter changes had minimal effects on the quality of the lithography.

The recommended dry-etch process showed that ASNR should perform as well as - if not better than - commercial CMS, giving a 1-micron process with good edge acuity. The exposed result was shown to be stable in air for up to three months, and capable of submicron lithography with appropriate changes to process parameters such as dose and bias. Typical results of a process improvement are shown in Figs 3.3.1 and 3.3.2 where an intermediate MIBK/IPA rinse after MIBK development reduced resist swelling and improved edge acuity.

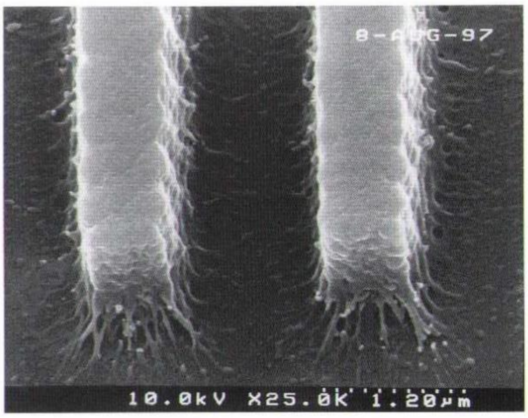


Fig 3.3.1 ASNR resist developed in MIBK with no intermediate rinse

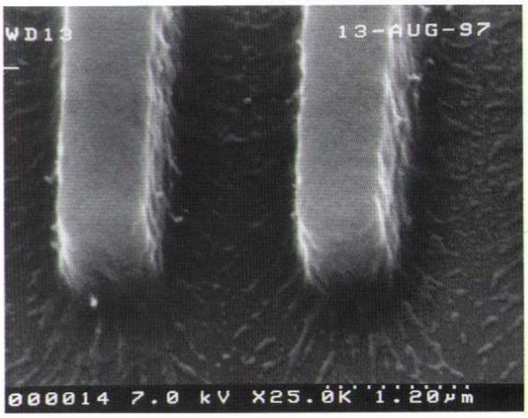


Fig 3.3.2 Effects of intermediate rinse

3.4 Field Emitter Devices

The CMF has carried out a two year research programme on field emission devices in collaboration with Oxford University. The aim of this EPSRC-funded programme, which ended in December 1997, was to investigate porous silicon as a candidate material for flat screen display applications.

Field emission devices were fabricated in both single crystal and polycrystalline silicon, after which they were anodised for conversion into porous material. State-of-the-art equipment at the CMF, including high resolution electron beam microfabricators and plasma dry etching systems, were used to produce high quality devices. A wide range of experiments were carried out at RAL under ultra high vacuum conditions to assess the performance of the fabricated devices, both before and after anodisation.

During these experiments, up to 5 µA of emission current was obtained from single emitters, while multi-tip arrays yielded up to 100 µA, both at 80 volts grid bias. Life-time tests were carried out for over 1100 hours of continuous operation without degradation of the emitters. Following the anodisation process, the operating voltage could be reduced by 20% and an improvement in the emission uniformity was established. These results confirmed that the fabricated field emission devices were both robust and of high quality.

The success of the project has received considerable attention from both the academic and industrial communities in the UK and abroad. Fig 3.4.1, for example, shows a 40 x 40 array of FEDs, made for the Open University for use as an electron source in a novel 'mass spectrometer on a chip'. Also, there are plans to produce silicon field emitter devices in various configurations at the CMF, for experiments at the Universities of Cambridge, Birmingham and Nottingham.

In addition, two SME display companies, Ceravision and PFE, are now based at Rutherford Appleton Laboratory to use CMF equipment and expertise in the development of flat screen displays, as described below in Section 6.

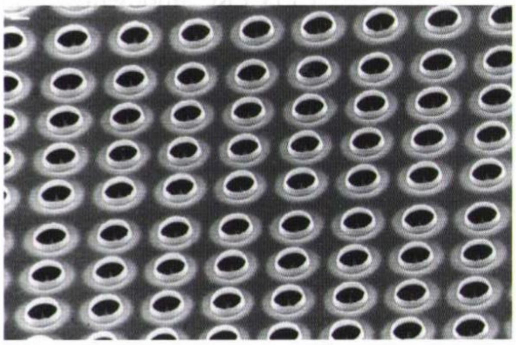


Fig 3.4.1 Array of 40 x 40 field emitter devices at 7 µm pitch as supplied to the Open University

4. UK Collaborations

4.1 LIGA Activities

Three-dimensional microforming using deep X-ray lithography has remained an important activity in CLRC, and X-ray mask-making continued at CMF, with many masks being supplied to customers for exposure at the Daresbury Laboratory. Previously, these used 125 mm polyimide as the substrate membrane, but these masks have a relatively low lifetime in the X-ray beam, primarily due to thermal expansion of the polyimide. This year the manufacturing process has been improved to include 0.5 - 0.6 mm beryllium membrane substrates for critical applications, although the original polyimide mask type is still available for low-cost, single-exposure experiments. Although more costly, these new masks have a greater transparency to the X-rays in the clear field areas and considerably greater lifetimes. Fig 4.1.1 shows an SEM photograph showing some features of a typical gold-on-beryllium X-ray mask ready for shipping to Daresbury for X-ray exposure.

Although X-ray mask-making continues to use standard chrome-on-glass photomasks and an optical mask-aligner giving a minimum feature size of 2 - 3 microns, an electron beam direct-write process, which should reduce costs and improve resolution, is currently being developed.

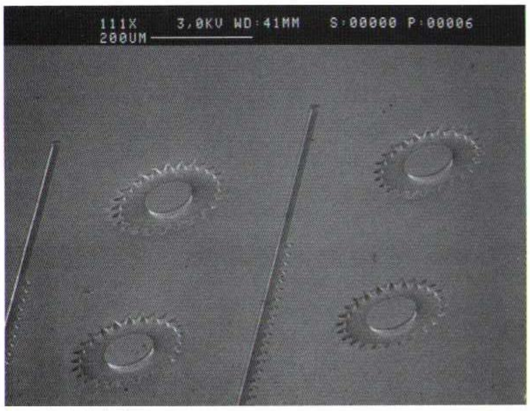


Fig 4.1.1 SEM photograph of some typical gold features on a beryllium membrane LIGA mask

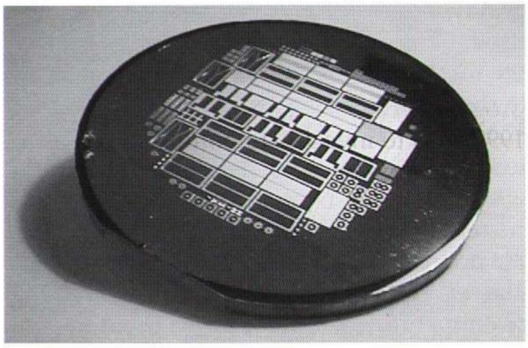


Fig 4.1.2 A typical 200 mm LIGA mask fabricated at the CMF

The LIGA Club consisted of industrial partners BICC, BNFL, Oxley, Rover and Lucas, along with de Montfort University and the CMF groups at RAL and Daresbury. The three year project was successfully concluded in 1997, having achieved its main objectives. In particular, UK industry has been introduced to the technology at an early stage, and prototype industrial products have been used as a demonstrator. The CMF now markets an electron beam written LIGA mask (Fig 4.1.2), fabricated on either polyimide or beryllium which can be exposed at a number of X-ray synchrotrons in Europe. The Daresbury synchrotron has an experimental X-ray beam with a simple home-built scanner able to expose experimental devices.

4.2 OPTIM

This two year EPSC-DTI Link project started in September 1995, CMF's partners being Bookham Technology Ltd, Druck Ltd and the Ford Motor Company. The aim of the project was to develop an in-cylinder monitoring system for automobile internal combustion engines, and RAL was involved in both modelling studies and sensor design. Successful test-bed operation was achieved by April 1997, and since then CMF has concentrated on improving the bonding techniques involved.

Two bonds are needed - between a signal-carrying glass fibre and a glass ferrule, and also between silicon and glass in a 'sandwich' that forms the pressure sensor itself. These bonds must withstand both the mechanical and thermal stresses found in the fairly harsh environment of a typical IC engine. In the 'Anodic Bonding' technique that was used, the work piece was heated to 200 - 400 °C while an electric current of up to 600 V was passed through the bond. A number of epoxy resins, solder glasses, etc were investigated over a range of temperatures and voltages. Bond strengths were tested by straightforward mechanical means and generally the best results were achieved by bonding temperatures towards the top end of the above range.

Fig 4.2.1 shows a glazing profile for DP2600 glass solder for fibre attachment. The solder is supplied as a solid powder so two heating cycles are needed - first to 'glaze' (ie, melt) the powder and then to allow insertion of the fibre, followed by a slow annealing process to minimise internal stresses.

The 'silicon-glass' sandwich generally had a bond area of 2 x 5 or 2 x 10 mm and the required temperature depended on the glass thickness. Fig 4.2.2 shows a typical Current vs Time plot for a bond area of 2 x 5 mm at 400 °C and 600 V.

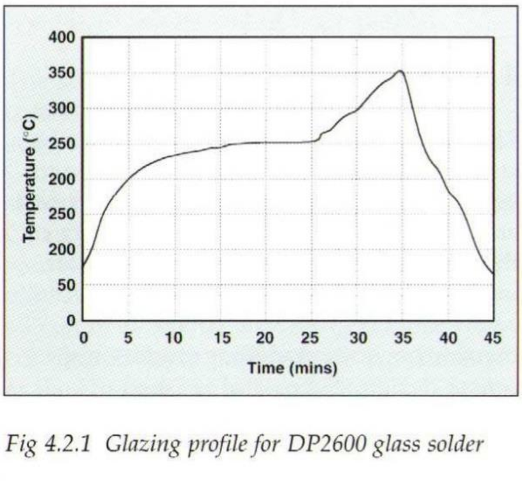


Fig 4.2.1 Glazing profile for DP2600 glass solder

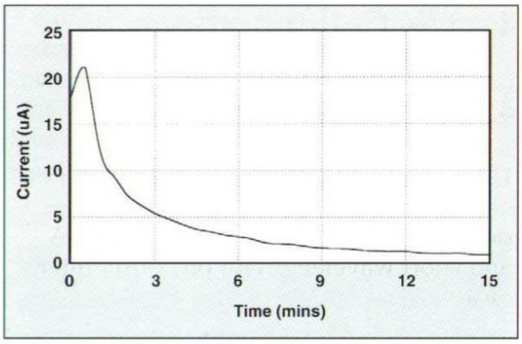


Fig 4.2.2 Anodic bonding current characteristics at 400 °C and 600 V

4.3 Pupil Filters

An EPSRC funded project to investigate the use of phase filters in collaboration with Oxford University was successfully completed, and demonstrated enhanced performance at a wavelength of 248 nm.

High resolution optical lithography is used principally in the semiconductor industry for producing microprocessors and memory chips. Conventional projection systems use a lens consisting of many elements with a stop in the centre. The stop is a clear aperture which restricts the rays passing through the system to give the required numerical aperture (NA).

The demands of the industry for ever-greater resolution have led to the use of shorter wavelengths and higher numerical apertures. This in turn means that the focal plane has to be kept within tighter tolerances, according to the Rayleigh criterion:

$$\text{Depth Of Focus (DOF)} = 0.5 / \text{NA}$$

One possible way of improving the DOF beyond the Rayleigh criterion is to insert a transparent plate in the stop position of the lens. On this plate, specially designed patterns are placed. These patterns are of the same material as the rest of the plate but are raised by $\lambda/2$ above its surface, where λ is the wavelength. This places a controlled phase variation on the incoming wavefront, increasing the DOF by as much as three times. Such a plate is called a *phase filter*, and a typical example is shown in Fig 4.3.1.

The principle has already been demonstrated at Oxford University at 633 nm. In the CMF, a complete optical projection system was built at 248 nm with a lens of NA 0.47. The results from these experiments have been tested on one filter already and have successfully demonstrated the principle for high NA and short wavelength for one pupil filter design. Fig 4.3.2 summarises these results, comparing the ranges of acceptable CD values (0.5 µm ± 10%) for systems with and without phase filters. (Note that 'lens-only' focus values have been increased by 0.6 µm for clarity.)

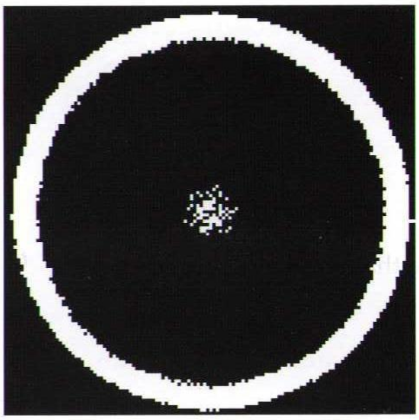


Fig 4.3.1 Example of a Phase Filter as used to increase Depth of Focus

The work will now be extended to at least two other filter designs and also to demonstrate the effect of a phase filter placed outside the lens. If successful the latter may prove more commercially attractive, with possible applications in the manufacturing of semiconductors and Compact Disks.

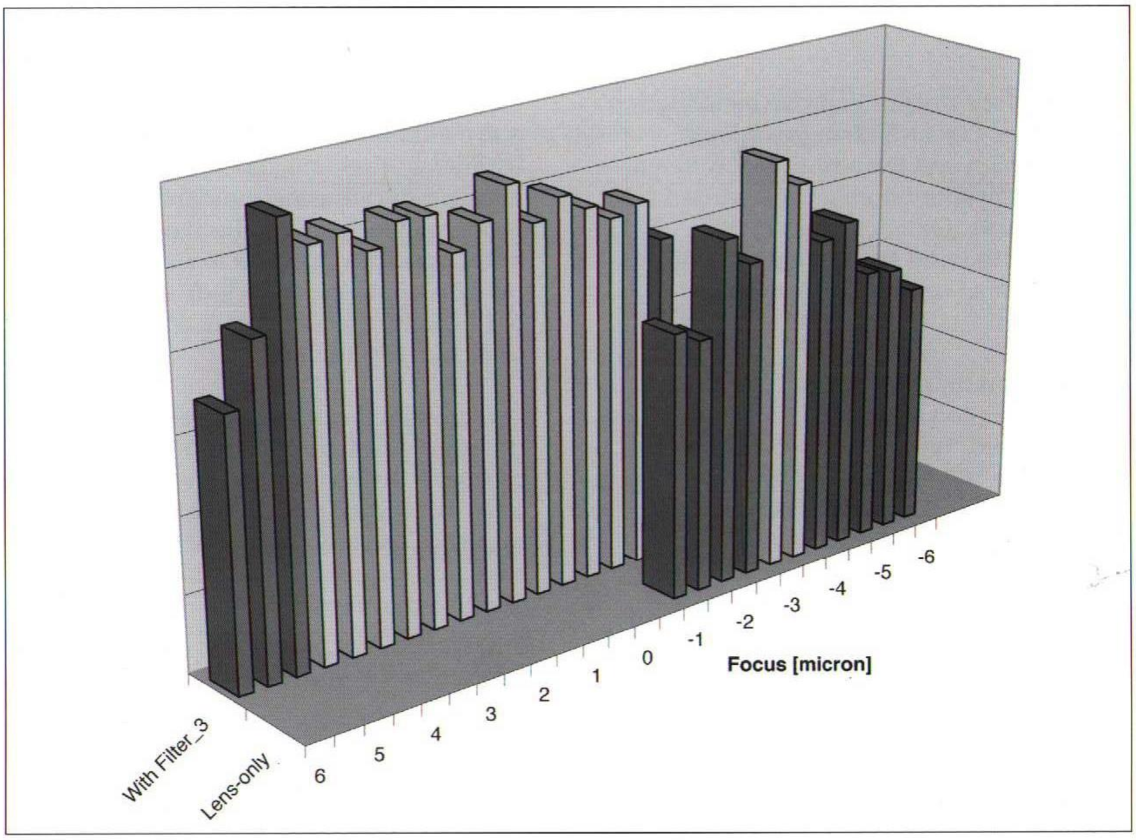


Fig 4.3.2 Critical Dimension as a function of defocus for lens-only (front) and with-filter (back) systems. Lighter bars indicate acceptable range of CD values. Lens-only focus values shifted by +0.6 µm for clarity

4.4 Electromigration consortium

The continuing drive towards ever smaller critical dimensions in the Integrated Circuit industry, and customer demands for higher reliability, have both led to the need for higher operating frequencies, greater circuit complexity and reduced power consumption. As gate lengths approach 0.25 µm or less, there is a corresponding need to decrease the widths of the interconnecting tracks and to increase the number of interconnect levels. This leads to higher current densities and a greater susceptibility to track failure. Thus, metallisation processes of ever higher quality are needed.

At high current densities there is a significant transfer of momentum, from the electrons which make up the electric current, to the metal ions in the tracks themselves. This *electromigration* is thought to be one of the principal causes of voiding and hillock formation in the interconnecting metal tracks, resulting in circuit failures.

Key developments to improve metallisation performance include changes in basic circuit design and the addition of different alloys to the aluminium currently used for metallisation. Other changes include different processes such as grapho-epitaxy, and the use of copper rather than aluminium.

The consortium investigating electromigration consists of the Universities of Newcastle, York, Lancaster and Cambridge. CMF's role has been to design and fabricate test structures of various complexities using electron beam lithography and plasma dry etching. So far, several hundred devices have been produced in fully packaged versions and delivered to the various universities for analysis.

4.5 Micromultipede

Materials with different coefficients of thermal expansion, combined in a sandwich cantilever structure, can form very effective elements of micromechanical actuators. Thermally operated, these have a variety of applications including temperature controlled electrical switches and sensors.

A novel use of this structure is a multicantilever array where each element can be actuated in sequence to produce movement, giving a 'walking micro robot' or *micropede.* The actuation is provided by micro heaters, built into each cantilever. Using a whole-wafer modular approach, a power supply, control electronics, and a basic communication system could be built on one face of the wafer, with the back-plane being used for an array of cilia with integrated micro heaters.

CMF, together with Cardiff University, proposes to develop a novel system in which one or more 'walking' micropede units will form a mobile microsystem, carrying on-board power, sensor, control and commmunication functions. Ultimately, these micropedes could be mass-produced using standard silicon processing techniques. Each one would be a few square millimetres in size, and possible applications include the inspection of internal surfaces of pipes and extra-terrestrial exploration.

As a preliminary demonstration, CMF has designed and fabricated some bimorph cantilever arrays using a novel microfabrication technique in a variety of materials, as shown in Fig 4.5.1. The actuation sequence for locomotion is illustrated in Fig 4.5.2.

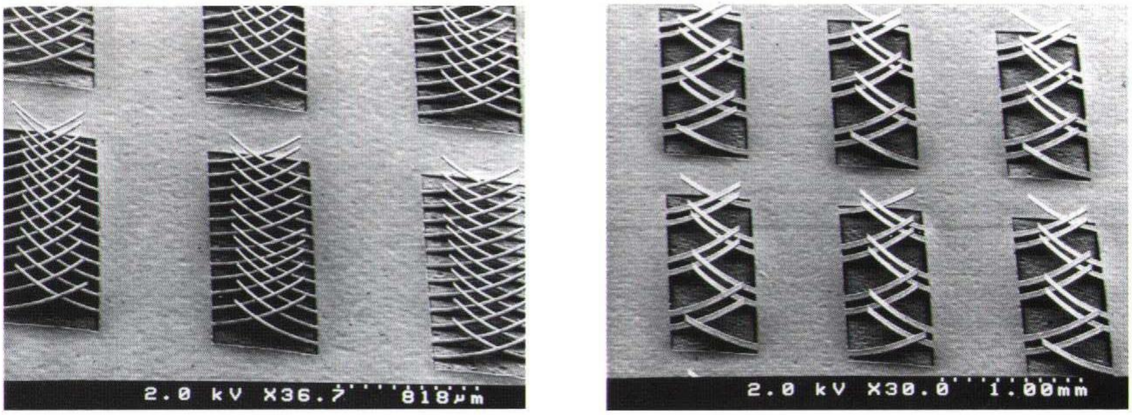


Fig 4.5.1 Micro cantilever arrays produced at the CMF by a novel surface micro-machining technique

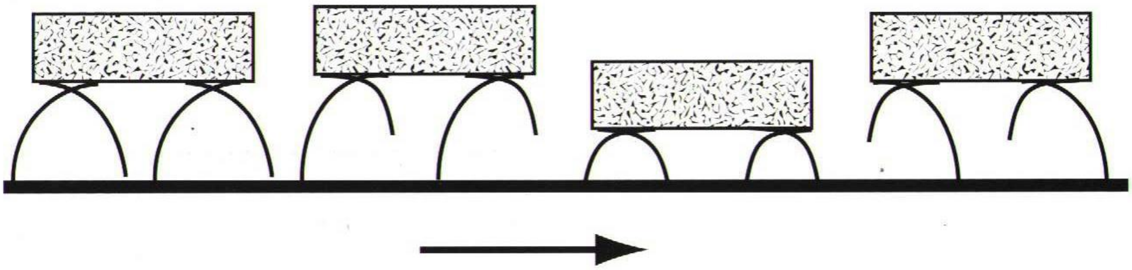


Fig 4.5.2 Actuation sequence for a micropede showing cilia operation

5. Other Collaborations

5.1 NANCAR

NANCAR is an ESPRIT research project which aims to establish industrially compatible e-beam lithography processes based on commercial chemically amplified resists (CARs). CMF is the project co-ordinator and the other partners are CSELT and CNR-IESS (Italy), Sigma-C (Germany) and NCSR-IMEL (Greece). The project began in January 1996 and the second annual review meeting was due in April 1998.

Good progress has been maintained during the second year of the project, with processes being optimised at 150 nm resolution for all three commercial CARs (AZPN114, SAL601 and UVIII) for all types of feature. Prototype processes have been established with a resolution of 100 nm or less, and sub-50 nm resolution has been demonstrated for all three resists. The ultimate target resolution of 30 nm with high aspect ratio has been obtained for AZPN114, as shown in Fig 5.1.1. Similar results include sub-50 nm lines in UVIII resist (Fig 5.1.2) and 100 nm pillars of SAL601 (Fig 5.1.3).

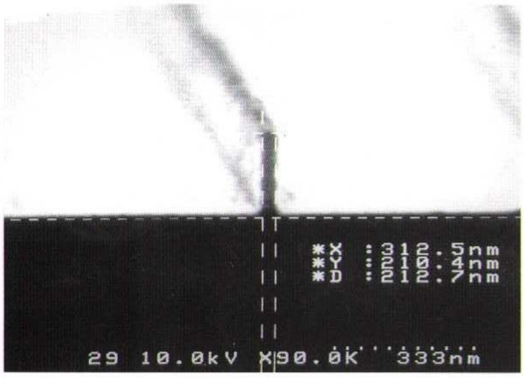


Fig 5.1.1 30 nm AZPN114 negative resist lines with 7:1 aspect ratio

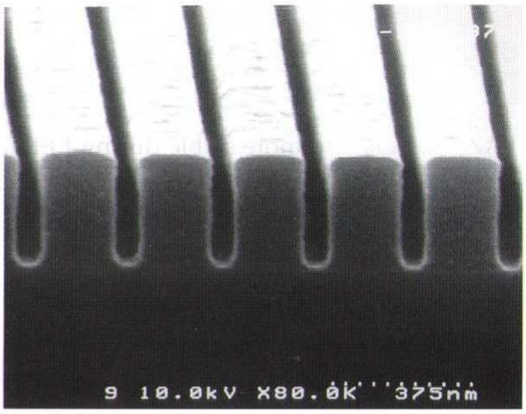


Fig 5.1.2 Sub-50 nm lines in UVIII positive resist

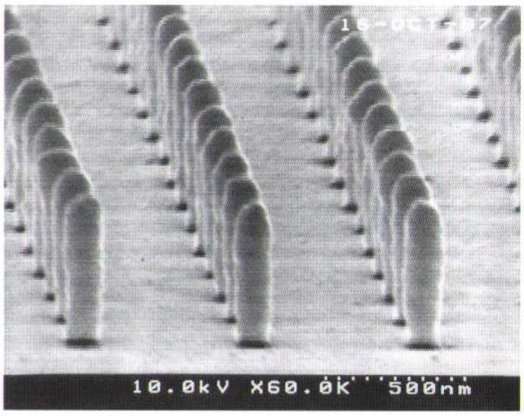


Fig 5.1.3 100 nm pillars of SAL601 resist

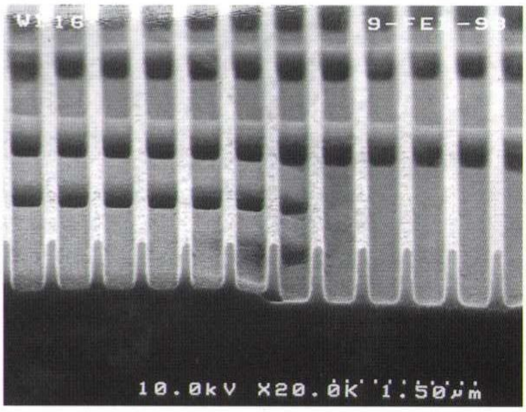


Fig 5.1.4 150 nm lines of AZPN114 on existing structures on a 6″ industrial wafer

The most critical issues concerning CARs for industrial application, such as the effects of post exposure bake (PEB) and post exposure delay (PED), have been investigated, with the conclusion that AZPN114 has better sensitivity, contrast and resolution capability than SAL601. AZPN114 is also more stable during PED but it requires very strict control of PEB temperature fluctuation. The positive UVIII resist demonstrated high resolution capability and stability in both PEB and PED processes.

A 6" industrial wafer from SGS Thomson Microelectronics has been exposed in CMF's VB6-HR e-beam system at 100 kV. In total, 132 dies of size 5 x 5 mm with 150 nm lines were exposed on the wafer using AZPN114 chemically amplified resist. The CD variation across the whole wafer is within 10% of the nominal CD value of 150 nm and Fig 5.1.4 shows some typical lines on top of existing WSi topographical structures on the industrial wafer.

5.2 MICROSYNC

Microsync is an EU-funded TMR ('Training and Mobility of Researchers') project involving twelve partners in nine European countries. It started late in 1997 and is a three-year programme whose aim is to develop deep X-ray lithography, the core process in LIGA technology, into an industrially viable process. It involves the development of microfabrication techniques, using synchrotron radiation, by performance enhancement and combination with other technologies.

The project also aims to create a team of experts in Europe through exchange visits and training. The development and sharing of this expertise should lead to improved European competitiveness and job creation.

Several research objectives have been outlined in the Microsync project to achieve these goals, including:

- increased process efficiency;
- establishing dimensional and methodological standards;
- developing design and simulation tools;
- increased material flexibility;
- making industrially-relevant components.

The CMF, in partnership with Daresbury Laboratory, is leading several tasks in the project, and these include:

- identifying X-ray irradiation times for higher throughput using novel photoresists;
- optimising the adhesion between resist and substrate;
- studying resist development processing;
- improving synchrotron irradiation conditions.

An additional task is to develop a novel 'mix and match' approach for microfabrication, using a combination of deep X-ray lithography and laser micromachining. As part of this task, CMF recently investigated the use of 248 nm laser ablation on a newly-available resist, SU-8.

5.3 ELLIPSE

CMF and Exitech Ltd have recently completed the first phase of an ESPRIT project called ELLIPSE. This is a large collaboration between various laboratories and companies in Europe, including GRESSI, IMEC, ASM-L, Zeiss, Heraeus, Lamba-Physik, Korth and Exitech. The principal goal of the project, which ended in July 1997, was to develop a 193 nm stepper for the next generation of optical lithography.

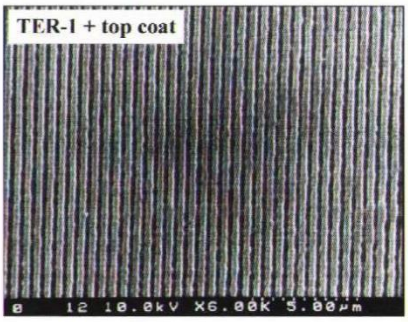


Fig 5.3.1 0.25 µm lines and spaces in TER-1 resist, obtained with new 193 nm micro-stepper

CMF has a comprehensive simulation package, PROLITH/2, which was used to model the resist profiles after exposure to

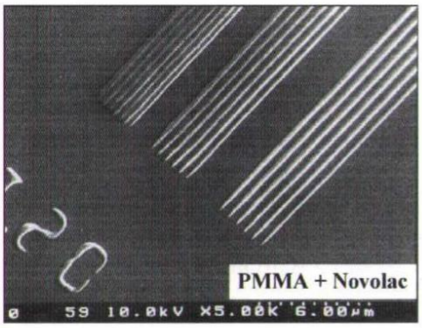


Fig 5.3.2 0.2 µm lithography in PMMA on novolac resist in ELLIPSE project

the aerial image and subsequent wet development. Exposures were made by Exitech on their micro-stepper at RAL.

This micro-stepper consists of an excimer laser, whose natural bandwidth has been reduced from 300 to 0.5 picometre, high resolution spectrometer, beam profiler, dose controller, autofocus and aerial image measuring capability. The workpiece temperature is controlled to within ±0.2 °C.

Results obtained so far have been published at the 193 nm Conference in Japan. For the experimental TER-1 positive resist, patterns with 0.25 µm lines and spaces have been obtained, as shown in Fig 5.3.1. For PMMA, the best results were obtained with novolac resist as an antireflective layer as shown in Fig 5.3.2.

5.4 EUROPRACTICE

Europractice entered a second two-year phase on 1 October 1997 with a modified structure and a number of new Service Providers. The Central Microstructure Facility was designated host for the new Coordination Office, chaired by Professor Lawes, and lead partner for Competence Centre 4.

Europractice was set up by the European Commission to facilitate the acceptance and use by industry, institutes and universities of microelectronics and microsystems technologies and its second phase is designed to continue this process. A number of Service Providers cover Integrated Circuits, Multi-Chip Modules, Microsystems (MST) and Training, each aiming to achieve self-funding by the end of the period.

The Coordination Office

The Coordination Office is an innovative feature of the second phase. It advises the Service Providers, monitors their activities and reports to the Commission. It also disseminates information on Europractice and its technology projects through publications, exhibitions and conferences. The Office contributed to 'MST News' and mounted displays at a number of key exhibitions such as Intertronics, the Hannover Fair and Analytica. A Europractice web site giving information on Europractice and its Service Providers was created by the Office very early in the current phase and a publicity flyer has been distributed widely. The Office hosted a Service Provider workshop at Magdalen College, Oxford when plans for achieving the aims of Europractice were discussed and agreed.

Benchmarking European industry capabilities against those of the USA and the Far East is a continuing activity involving Nexus, the European Network of Excellence on Multifunctional Microsystems, and Europractice. Professor Lawes was a member of a group which visited a number of MST organisations in the USA.

Competence Centres 4 and 5

A further innovation was in the Microsystems area where six application-based Competence Centres (CC) were established to complement the provision of proven technologies by the industry-based Manufacturing Clusters. The Centres are mainly concerned with design and prototyping and CMF is the lead partner in CC4 'Process control, machine tool manufacturing, micro-actuators and micromachines' and associate partner in CC5 'Microfluidic systems'.

The Competence Centres provide:

- free consultancy, feasibility studies and project evaluation;
- brokerage, in-house design and microfabrication services;
- routes to prototyping, using facilities

available in European institutes, Europractice Manufacturing Clusters and industry;

- routes to large scale manufacturing;
- collective information on processes and technology suppliers.

CMF began its work for CC4 by establishing a database of service providers across Europe. Two reports were compiled - one on services offered by the Manufacturing Clusters and the other listing those by non-Europractice companies. The purpose of these reports is to ensure that customers can obtain the best service and products in Europe. To this end, efforts were made to disseminate information on Europractice and CC4 services to a wide audience: for example, the CC4 web site was set up and a CC4 brochure and poster produced. In addition, CMF contributed to CC5 by compiling a comprehensive knowledge base on microfluidic devices.

The proactive seeking of new customers is a key feature of the Competence Centres. Previously, CMF provided services mainly to UK university users but the Competence Centres are set up to serve European industry as a whole, especially SMEs (Small and Medium-sized Enterprises). Potential users of CC4 technologies are mainly in non-MST industry. Customers are being contacted through visits, meetings, conferences and exhibitions. Twenty-eight new customers were contacted and nine meetings held to discuss their requirements. Three quarters of the new customers are from industry, many of them new to MST. These include the food, pharmaceutical, chemical and toy industries. Enquiries have been received from customers in the UK and from Ireland, the Netherlands, Spain and Sweden via the internet. Three feasibility studies have been conducted, one resulting in a funding proposal for further exploitation.

Information on Europractice can be found at the web site at

http://www.europractice.com

which also links to web pages for the Coordination Office and Competence Centres 4 and 5.

Manufacturing Cluster

The UK Manufacturing Cluster, led by GEC with the CMF as partner completed its programme in September 1997 and was replaced by a new Consortium.

5.5 Semiconductor Equipment Assessment (SEA)

The Semiconductor Equipment Assessment initiative was set up by the European Commission in 1996 to help ensure that

300 mm Projects - Evaluation at User Sites				
Theme	Project	Subject	Supplier	Users
Metrology	FLASH PT300	Fully automatic ellipsometer for 300 mm wafers	PLASMOS	GRESSI ST SELETE I300I
Cleaning/ Environment	CFC	300 mm pod & open cassette centrifugal cleaner	DMS	ST I300I
Automation	POCS	300 mm front opening pod & cassette sorter	RECIF	INCAM I300I Intel
Test	AUTOPSY	Automated 300 mm prober system	Karl Suess	FhG-IIS-B
300 mm Projects - Demonstration Tests at Equipment Manufacturer Sites				
Hot Process	IMAN 300	RTP implant annealing	STEAG AST	SIEMENS GRESSI
Cleaning/ Etch	WM 303	Single wafer front & backside etcher	SEZ	I300I
Sputtering	FF300	High aspect ratio sub micron hole fill	TRIKON	SIEMENS
Ashing	RAPID	High throughput low CoO, low damage batch asher	TePla	SIEMENS

Table 5.5.1 300 mm wafer projects

new European equipment and innovative process techniques meet the needs of semiconductor manufacturers world wide, avoiding the gap between innovation and production which can occur when technologies are evolving rapidly. New equipment and processes are assessed at production facilities and global dissemination of the results to potential purchasers is vital. This dissemination activity is centred at CMF and its success has led to funding for a new programme (SEA300) demonstrating prototype equipment aimed specifically at the production of semiconductors using the next generation of silicon wafer, ie 300 mm diameter. CMF is the focus for SEA300 dissemination and for project selection and control while Gressi/CNET in Grenoble supplies 300 mm wafers and metrology/analytical services.

Currently there are 37 projects - 26 on equipment for wafers up to 200 mm in size, ten on 300 mm equipment and one on flat panel displays. The projects involve 25 European equipment companies, 33 industrial users from Europe, the USA and South East Asia and five major European industrial research organisations. About half of the 200 mm projects (cf CMF Annual Report 1996/7) have been completed and benefits identified in technical performance, productivity and marketing impact. Table 5.5.1 lists the growing number of 300 mm projects currently under way, again covering a wide range of subjects.

SEA Results

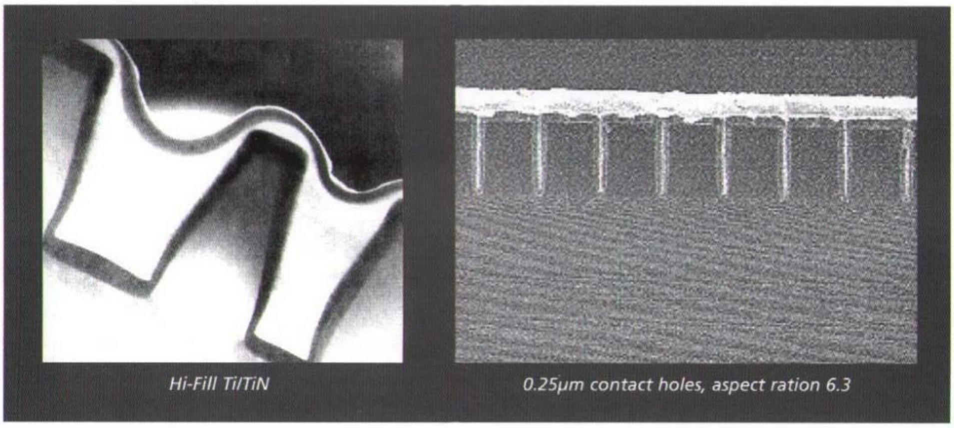
Two examples are given. In the first, the equipment is based at a major semiconductor manufacturing plant. In the second, a concept at an industrial research institute has evolved to full commercialisation.

Project Forcefill

This project was set up to assess the innovative Forcefill™ sputtering system produced by UK manufacturer Trikon to fill wafer contact holes and vias with aluminium at high pressure (Fig 5.5.1). The equipment was installed at TI Freising, a US-owned production facility, which runs a 0.5 µm multilayer metal BiCMOS process. Ericsson AB is the other partner.

Extensive use was made of reliability testing methodologies to identify failure mechanisms using Marathon and Ironman reliability testing methodologies (Fig 5.5.2). The accumulated data resulted in improved design and procedures.

The data clearly shows the improvement in tool performance realised during the project with mean time between failures rising progressively to 232 hr. Availability for Operation (AO) approached 90% and and uptime exceeded 90% (AO + wait time). This project has demonstrated that the complex cluster tool, including the Forcefill process, is fully compatible with the demands of the modern, high volume fab.



Hi-Fill Ti/TiN

0.25µm contact holes, aspect ration 6.3

Fig 5.5.1 Contact holes (left) containing Ti/TiN and (right) completely filled with aluminium using the Forcefill™ high-presure process after being lined with asputtered Ti/TiN barrier

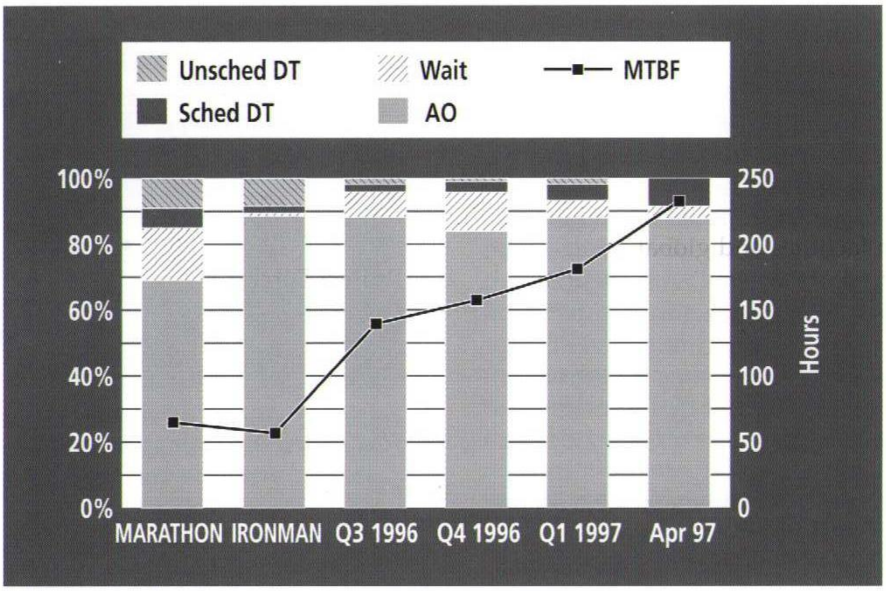


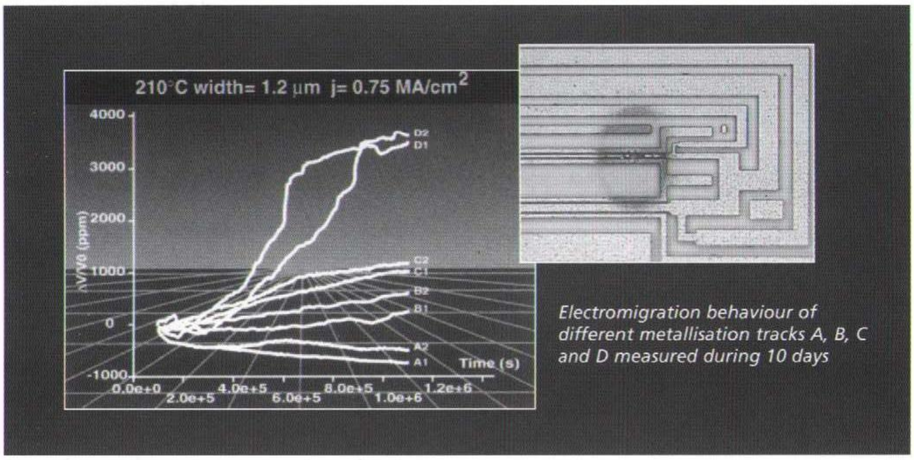
Fig 5.5.2 Performance improvements logged during project FORCEFILL

Exhaustive device level tests have also proved the Forcefill process to be a robust, controllable technology for low resistance vias with superior electromigration performance in advance of conventional metallisation techniques.

Project EMMEA

The EMMEA partners are evaluating a very high resolution, electromigration test system manufactured by the SME company DESTIN. Rapid low cost electromigration testing is being achieved using innovative early resistance change techniques. The equipment is being evaluated at the Mietec site in Belgium and Philips and Siemens are partners.

An example of the use of the EMMEA system for the rapid evaluation of different metallisation structures is shown in Fig 5.5.3. The test time was reduced by a factor of four, reducing significantly the important Cost of Test. Another benefit is that the stress conditions for accelerated life test can be reduced by a factor of 3 to 10, reducing the possibility of erroneous failure conditions occurring. The system has also been demonstrated on bond ball reliability for automotive power products. This project has brought a small company, which originated in a research institute, into close cooperation with large semiconductor companies.



Electromigration behaviour of different metallisation tracks A, B, C and D measured during 10 days

Fig 5.5.3 Electromigration in metallised structures

5.6 RAL-KIST JRL

'JRL' (Joint Research Laboratory) is a combined research initiative between RAL and the Korean Institute of Science and Technology (KIST). The initiative began in Summer 1997 and a Memorandum of Understanding was signed by both parties in London the following October. Fig 5.6.1 records this event, showing the joint signature by Dr P R Williams (L) and Dr Oh-Kwan Kwon (R), watched by Prof R A Lawes, Dr Boo-Sik Yi and the Minister for Science, Mr J Battle.

JRL aims to promote collaborative research in MEMS (Micro Electro Mechanical Systems), concentrating on four main areas as follows.

- Microactuator Technology
- Field Emitter Devices
- Millimetre Wave Technology
- Microtribology

CMF is heavily involved in the first two of these topics. Examples of microactuator technology include the Micromultipede and UV-LIGA processing featured elsewhere in this Report (Sections 4.5 and 4.1), while Field Emitter Devices (Section 3.4) have been a CMF research topic for over three years.

Other microactuator projects include an atomic 'toothbrush' for an atomic force probe array (toothbrush-like) to allow parallel imaging, and a micromotor using ultrasonic travelling waves to excite PZT thin film as the driving mechanism.

Fig 5.6.1 Signature of the JRL agreement by the Director of CLRC and Vice President of KIST

Microtribology, however, is a new area of research for the Rutherford Appleton Laboratory. Here, various microfabrication techniques will be employed to create well-defined three dimensional features on material surfaces, which will be used with different lubricants to study their rheological and the effects of 'wear and tear'. Surface preparation will involve CMF's expertise in microfabrication.

6. Industry at the CMF

6.1 Bookham Technology

Bookham Technology is a rapidly expanding company that designs and manufactures high performance integrated optical circuits. For many years Bookham was based at RAL, but after a period of tremendous growth it moved to larger premises at Milton Park in July 1997. The CMF played a vital role in assisting and supporting Bookham Technology in its early years and the company still uses CMF facilities for work on development projects.

In November 1997 Bookham completed its most successful round of investment to date, yielding a total of $18.1 million. This was the company's third investment round bringing the total raised so far to $37 million.

Early in 1998 Bookham opened its new $10 million silicon wafer fabrication line to meet the needs of customer demand for ASOC™ products. The manufacturing facility is a combination of silicon processing and packaging, and is capable of producing 500,000 devices a year. The 14000 sq ft facility enables close control of the entire process, which results in superior quality products. Fig 6.1.1 shows a laser attach rig being used in the new Milton Park premises.

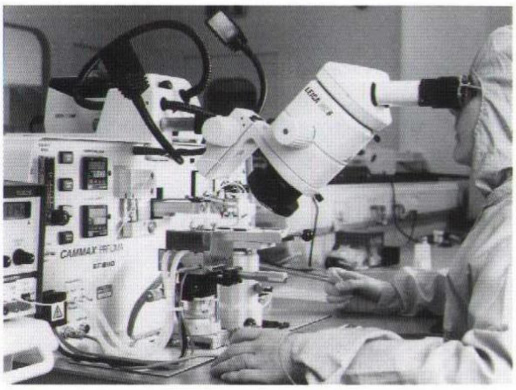


Fig 6.1.1 Laser attach rig at Bookham Technology's new premises

ASOC™ technology is used to produce a series of products for access and DWDM (Dense Wavelength Division Multiplexor) network applications, and the sensor industry. Because of ASOC™ 's modular architecture, designed to be quick and simple to modify, customers can tailor Bookham's standard products to better serve their specific requirements. During the last year Bookham launched a further two product ranges. The latest range includes transceiver devices for the access network that integrate a transimpedance amplifier (TIA) into the packaging (Fig 6.1.2). This is of significant importance to customers, allowing them to reduce the number of components required in a network and also to increase the distances between transceivers.

Although Bookham is an established high-volume manufacturer, the company is involved in continuous R& D. This development work includes future products for advanced telecommunications applications such as WDM (Wavelength Division Multiplexor) and optical networking, and also an array of specific customer-based projects.

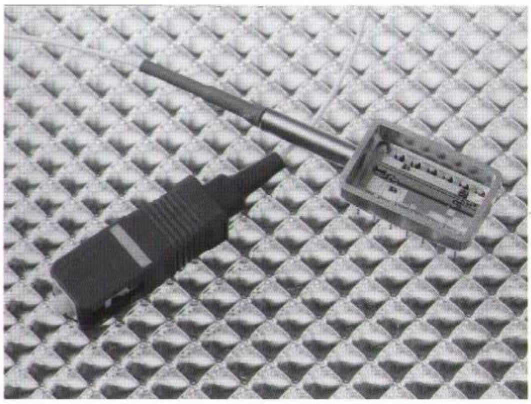


Fig 6.1.2 Bookham BKM-2420 family transceiver with integrated TIA

6.2 Ceravision

Ceravision Limited was formed to capitalise on developments in the sphere of field emission displays (FEDs). Whereas traditional displays use the bulky cathode ray tube - largely unchanged for a hundred years - most industry speculators predict that flat displays, such as those used on notebook computers, are poised to take much of this market.

By utilising a patented, innovative approach, Ceravision intend to overcome many of the limitations which have crippled flat screen displays in the past - ultimately licensing the technology for use in palmtop computers, large screen televisions, and even car dashboards.

In order to gain access to some of the world's foremost experts on FEDs, Ceravision have collaborated with the CLRC in a groundbreaking agreement. As part of this deal, the first of its kind, Ceravision have the use of £25m of capital equipment at the Rutherford Appleton Laboratory. The parties to this agreement, signed in March 1998, are shown in Fig 6.2.1.

By avoiding the pitfalls of venture capital, and relying instead on a select group of individual investors, Ceravision have retained autonomous control over their technology. This has proved to be highly successful, with Ceravision being awarded a SMART award by the Department of Trade and Industry, and rising to become the largest FED company in the UK in just two years.

Fig 6.2.1 Parties to the CLRC - Ceravision agreement. Back: Dr S E Huq, Ms Linda Baines, Dr A Reed (Commercial Director, CLRC), Prof R A Lawes (Director, CMF). Front: Mr T Reynolds & S Leigh (Ceravision)

6.3 Exitech

The 'Radiance Process' is a new, dry, laser cleaning process for the cleaning of many different types of substrate such as silicon wafers, masks, computer hard disks and optical components. The Radiance Process uses an excimer laser (which operates in the ultraviolet part of the spectrum) to remove particles as small as 50 nm from the surfaces by gentle irradiation with the laser, and a simultaneous gas flow that removes the particles once they have been lifted with the laser beam.

Laser cleaning is expected to be the next major advance in cleaning technology, having the potential to remove much smaller particles than conventional wet cleaning methods in the semiconductor, flat panel display and computer hard disk industries.

Over the last year, the 'Radiance Process' machine has been evaluated on computer hard disks, and calcium fluoride optics.

Computer hard disks are made of aluminium substrates that are coated with a thin layer of nickel-phosphorous compound, which is the magnetic medium. The surface of this needs to be polished in order to give it the required surface texture. The extremely small disk reader head floats at a height of 50 nm or less above the hard disk surface, requiring the removal of slurry particles, left over from polishing, down to at least this size. The microscope photograph in Fig 6.3.1 compares a residue of sub-micron sized diamond polishing slurry particles with a laser cleaned area.

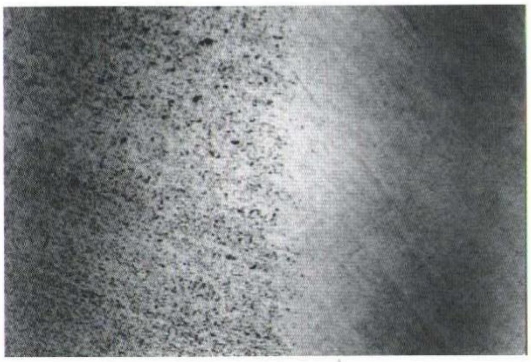


Fig 6.3.1 Sub-micron sized diamond polishing particles on computer hard disk surface (left) before and (right) after laser cleaning

Calcium fluoride lenses are used for optical lithography machines that use deep ultra violet light sources, such as an argon-fluoride excimer laser (wavelength 193 nm). At these wavelengths, quartz optics begin to absorb the radiation and a different material, such as calcium fluoride, must be used. The theoretical transmission of an uncoated calcium fluoride lens is 92.0% (including reflection losses) but polished lenses show in practice a transmission of only about 89.5%. This makes a large difference to the total transmission of a lithography lens assembly, which often contains up to 30 separate lens elements. 'Radiance Process' laser cleaning is capable of cleaning the lenses, by removing chemical contaminants and absorbed water, and increasing the transmission to the theoretical maximum value as shown in Fig 6.3.2.

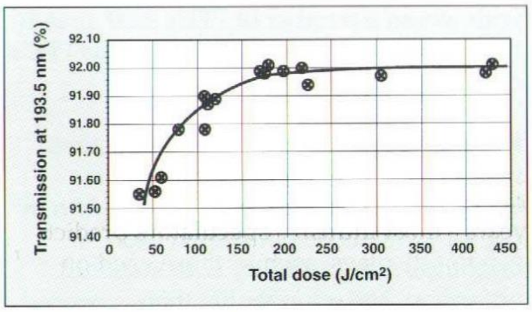


Fig 6.3.2 The effect of excimer laser cleaning, as a function of total laser irradiation dose, on the transmission of calcium fluoride

6.4 PFE

The high technology Field Emission Display (FED) company Printable Field Emitters Limited (PFE) relocated its development laboratory from North East England to the Rutherford Appleton Laboratory in February 1998. Following a recent £2m venture capital investment by 3i, Europe's leading venture capital company, PFE is now expanding its development team into its own private office and laboratory facilities at the Atlas Centre while enjoying access to other facilities within the Central Microstructure Facility. FEDs hold high promise as the next generation of flat display technology although conventional field emitter tips will be difficult to scale to large size at consumer prices. PFE's technology offers this exciting prospect.

The development of cutting edge technologies such as FEDs needs access to the clean room and other sophisticated processing facilities which are available in the CMF. It would be prohibitively expensive for an small company such as PFE to purchase such facilities. Furthermore, the CMF's Research and Development Group already works on field emission technology. PFE knew of RAL's commitment to partnership with the SME sector from its particularly successful relationship with Bookham Technology.

These factors, coupled with RAL's Oxfordshire location close to other high technology companies, the laboratories at Culham, Harwell and Oxford University -

with whom a number of PFE's staff already have close ties - meant that RAL was PFE's clearly preferred partner.

PFE has already built a simple structure, with three 2 mm x 2 mm pixels, at its Hartlepool laboratory and this is shown in Fig 6.4.1. It has demonstrated high brightness, compatibility with standard phosphors and a longer life than is needed for 1,000 line high definition TV applications. The partnership with RAL will help PFE to develop a 6 inch section of a 1 metre diagonal display, an important step before scaling up to large size takes place.

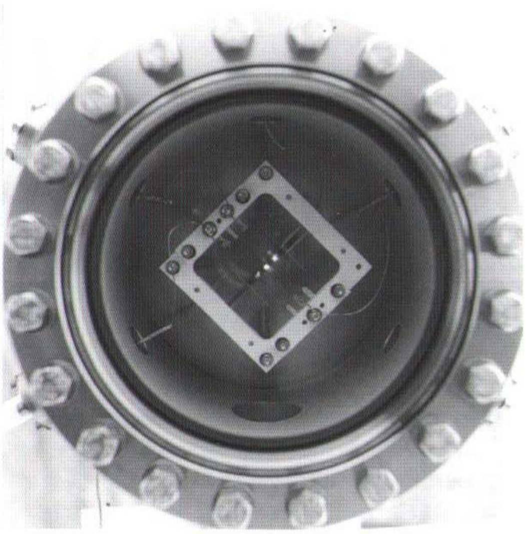


Fig 6.4.1 PFE's first demonstrator consists of three 2 mm x 2 mm pixels

6.5 Qudos

Qudos is currently working on two projects involving micro lenses. The first of these is the use of an array of micro lenses to focus ambient light onto a corresponding array of light sensors. This will provide an appreciable increase in efficiency of CMOS cameras. This increase in efficiency is essential for the higher definition camera chips where pixel sizes are smaller and non-active areas of the chip, such as metal tracks, have a larger fractional effect.

Currently, the process developed allows micro lenses to be produced consistently for 10 micron pixel arrays and further work is now being carried out on 5 x 3 micron arrays for both spherical and non-spherical lenses. The micro lenses themselves are made by baking arrays of rectangular blocks of photoresist. Figs 6.5.1 and 6.5.2 show the results of this 're-forming' process.

The key thrust of the development programme is to produce smaller lenses with minimal gaps between lenses (>0.5 µm) and to combine this with a colour process. This work forms part of a joint project with Nottingham Trent University and the CMF involving the development of low cost high resolution commercial devices such as head up and head mounted displays.

The second project involves the production of micro lenses for miniature displays and forms part of an MSc project for a Qudos - supported student from Swansea University. The lenses are formed over the emitting areas of the displays as shown in Fig 6.5.3 and are required to be of a multitude of shapes. The addition of micro lenses to miniature displays substantially enhances the technology.

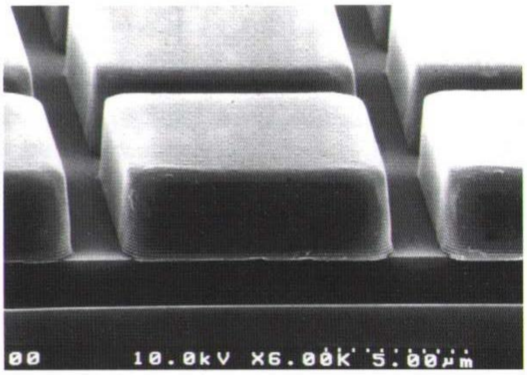


Fig 6.5.1 Array of micro lenses in photoresist before 're-forming'

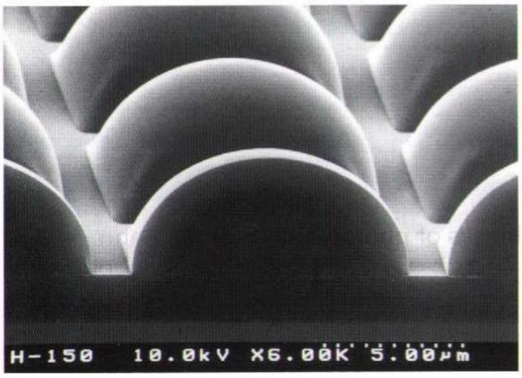


Fig 6.5.2 Re-formed array of micro lenses on 10 µm x 10 µm grid

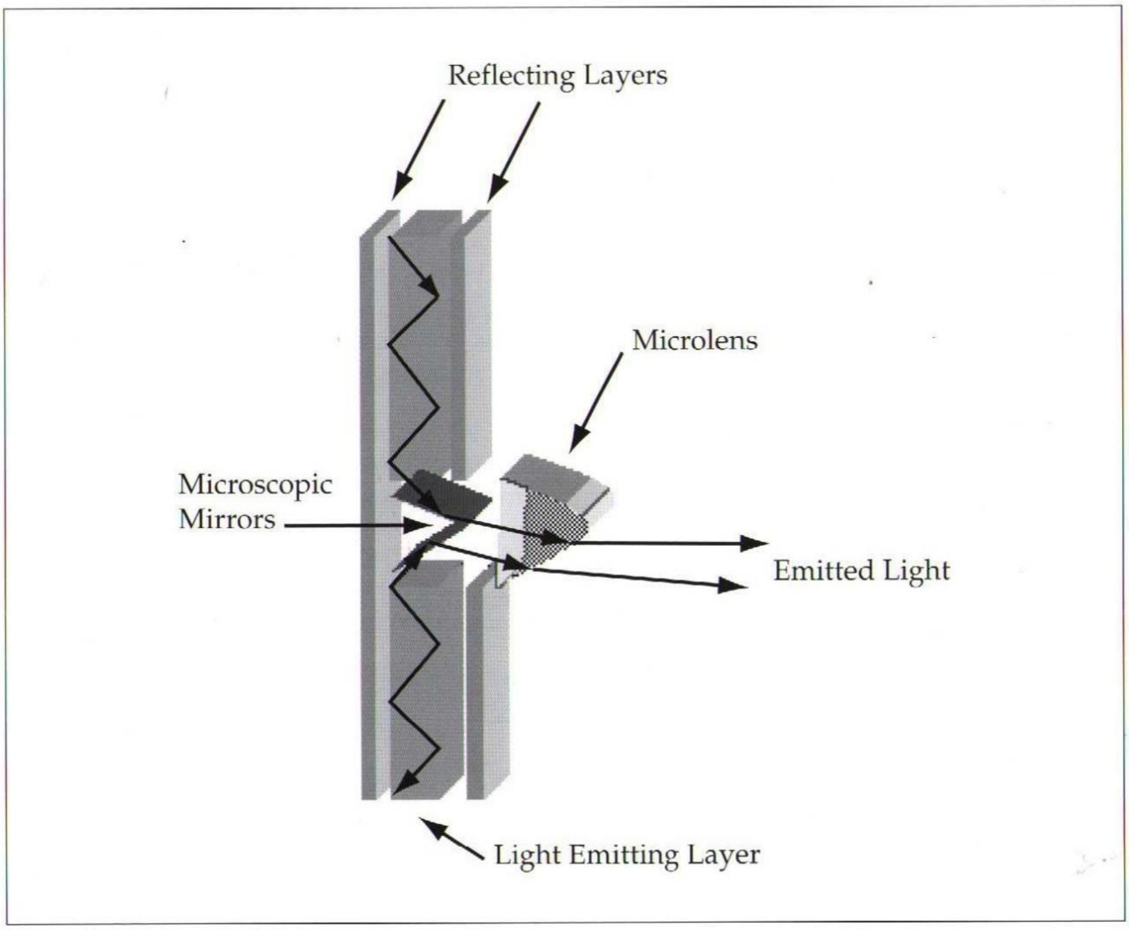


Fig 6.5.3 Micro lenses used to focus the output of a display

Appendix I EPSRC Grants and CASE Studentships

Grants and CASE studentships current during 1997/8 involving the CMF

Dr D W Allsopp, York
Enhanced electrorefractive effects in shaped quantum wells for optical modulation

Dr S R Andrews, Bath
Terahertz time domain spectroscopy

Dr K Barnham, Imperial College
Quantum well solar cells for thermophotovoltaic applications

Dr D Barrow, Cardiff
Nanostructured support media for analytical microsystems

Dr S Bending, Bath
Scanning hall probe microscopy studies of vortex dynamics and pinning in high temperature superconductors

Dr S Bending, Bath
A high resolution scanning hall probe microscope for ferromagnetic structures

Prof T M Benson, Nottingham
Optoelectronic components exploiting porous silicon materials

Dr N Braithwaite, Open
Tailoring the energy distributions of charged particles in low temperature plasma
Prof B Cavenett, Heriot-Watt
II-IV lasers and non-linear optics

Dr D Clark, Paisley
ROPA: optically activated and interrogatedmicro-machined microcalorimeter for gas sensing

Prof L Challis, Nottingham
Study of vertical tunnelling devices using phonon pulse techniques

Dr P A Childs, Birmingham
Coulomb transistor

Dr A Cordery, Oxford Brooks
Diamond (DLC) coated field emitters

Dr N Cronin, Bath
Terahertz waveguide and integrated component technology

Dr P Dawson, Belfast
Optical scanning probe microscopy in the meso to nanoscopic regimes

Mr V Djakov, Cardiff
Microrobotics

Mr A Dunbar, UMIST
Preparation and spectroscopy of microstructured photonic material

Prof L Eaves, Nottingham
Quantum transport and optical phenomena in GaAs/AlGaAs and self-organised semiconductor heterostructures

Dr J S Foord, Oxford
Diamond nanostructures: fullerene selective area growth compared to laser patterning for microengineering

Mr F N Goodall, RAL
Excimer laser fabrication of 3D microstructures; a basic study

Prof T Hall, King's College London
Reconfigurable optical switches for aerospace and telecommunications systems (ROSES)

Dr J J Harris, UCL
UCL Optoelectronics centre rolling grant

Dr S Haywood, Hull
GaSb/GaAs heterojunctions for thermophotovoltaic and solar cells

Dr J Hutchison, Aberdeen
Application of the Aberdeen SQUID/MRI receiver to the development of a compact low field imaging system

Dr R B Jackman, UCL
Diamond nanostructures: fullerene selective area growth compared to laser patterning for microengineering

Mrs J Jacobs, UMIST
Scanning probe microscopy for VLSI chips

Dr R Jones, Kent
Aqueous-base developable polymer resists based on the chemical amplification principle

Prof B Joyce, Imperial College
Interdisciplinary research centres for semiconductor materials 1996 - 1999

Dr S Kelly, Open
Field emitter for mass spectrometer project

Dr A J Kent, Nottingham
Direct Phonon studies of the carrier-phonon interaction & energy relaxation in quasi-ID electronic systems

Mr I Kennedy, Nottingham
SAW transducers made by EBL for FQHE studies at GHz freqencies

Dr M Lancaster, Birmingham
Superconducting antenna arrays

Dr E Larkins, Nottingham
Blue/UV lasers based on nitride semiconductors

Mr G Laws, Nottingham
Fabrication and characterisation of novel semiconductor lasers

Prof M J Lea, Royal Holloway and Bedford College
Properties of two-dimensional electrons in the fluid and solid phases

Prof M Lee, Imperial College
Cadium Selenide TFTS on plastic substrates

Prof D Mapps, Plymouth
A new nanoscale position sensing system

Prof D Mapps, Plymouth
Computer simulation of spatial noise fields in high performance thin-film magnetic tape heads

Dr G McHale, Nottingham Trent
Surface acoustic wave - liquid interactions

Dr C J Mellor, Nottingham
Phonon studies of low dimensional structures grown by the numbers syndicate

Dr A G Michette, King's College London
A laboratory scanning X-ray microscope

Dr R E Miles, Leeds
Processing of piezo ceramic films for GaAs monolithic microwave circuits

Prof D V Morgan, Cardiff
The design, fabrication & characterisation of visible LEDs

Dr A Mosley, CRL (EMI)
Display technology alliance

Mr A Naylor, Nottingham
Phonon studies of quasi one-dimensional systems made by EBL

Dr A G O'Neill, Newcastle
Reliability & design rules for deep submicron & power integrated circuit interconnect technology

Prof E G Paige, Oxford
Investigation of phase filters for enhancement of submicron optical lithography systems

Dr G Pan, Plymouth
A novel submicron trackwidth thin-film magnetic recording head with ion beam machined front gap

Prof D Payne, Southampton
The Optoelectronics Research Centre IRC rolling grant

Dr C Pegrum, Strathclyde
Advanced applications of high temperature thin-film superconducting devices

Dr R V Penty, Bath
Nonlinear asymmetric couplers for low power switching and integration

Prof E R Pike, King's College London
Superdense optical storage

Mr K Powell, King's College London
Diffractive Optics

Prof P D Prewett, RAL
Development of improved porous silicon field emitters for flat panel displays

Prof P D Prewett, RAL
Multiple-tip STM for surface imaging and nanofabrication

Prof P D Prewett, RAL
Investigation of phase filters for enhancement of submicron optical lithography systems

Dr A A Rezazadeh, King's College London
Study of novel KBT structures for high temperature applications

Dr A A Rezazadeh, King's College London
Study of InGaP/GaAs DHBTs for high frequency power applications

Dr W Schwarzacher, Bristol
Single mask to evaluate feasibility

Dr A J Seeds, UCL
All optical network channel synthesis using injection locked filtering & optical comb generation

Dr A J Seeds, UCL
Increased amplifier spacing for high bit rate soliton transmission using quantum well saturable absorbers

Dr S Sheard, Oxford
Integrated optics technology for instrumentation optics (IOTIS)

Prof K A Shore, Bangor
Infrastructure for chaotic optical data encryption

Prof K A Shore, Bangor
Packing & hybrid optical integration of laser diodes

Dr R W Smith, Imperial College
Excimer laser fabrication of 3D microstructures; a basic study

Prof S D Smith, Heriot Watt
Scottish Collaborative Initiative on optoelectronic sciences

Dr D P Steenson, Leeds
Monolithically integrated quantum barrier oscillators and mixers for millimetre-wave receivers at 180 GHz

Dr R Stevens, Nottingham Trent
Materials processing to maximise the outcoupling efficiency of micro-mirror LETFEL displays

Dr R Stevens, Nottingham Trent
Monolithic microlenses to maximise the optical coupling efficiency between LETFELs and optics

Prof R R Syms, Imperial College
Optimisation of bulk micromachined electrostatic actuators

Prof R R Syms, Imperial College
Microengineered optical read - heads and scanners (MORES)

Prof C Taylor, Leeds
Experimental validation of transient solutions for EHL point contacts with 3D surface features

Dr T Thornton, Imperial College
SiGe for MOS technologies (MICROPOWER)

Mr S Townsend, UMIST
Manufacturing discipline for multi-layer semiconductor devices

Dr J Tyrer, Loughborough
Surface modification using computer generated holograms for high power laser beam manipulation

Dr P R Unwin, Warwick
New ultramicroelectrode strategies for chemical in solution and interfaces

Dr B L Weiss, Surrey
Gratings & amplifiers fabricated in planar SiO_2 structures using ion implantation

Prof R Whatmore, Cranfield
Piezoelectronic motors for nanoengineering and metrology

Prof I White, Bristol
ROPA: Optical beam manipulation in two dimensional systems

Prof C R Whitehouse, Sheffield
Support for the Sheffield Central Facility for III-V semiconductors

Prof D Williams, UCL
Gas Sensors

Prof T Wilson, Oxford
A novel binocular 3D display and its uses in a study of the role of accommocation in human vision

Dr D Wood, Durham
Mask for 3D gyroscope

Dr J Woodhead, Sheffield
Enhanced functionality in VCSEL structures

Appendix II University Publications

Some publications arising from research which involved use of CMF

S R Andrews, P G Huggard, C J Shaw, A Cluff, O E Raichev, R Grey
Magnetic suppression of THz charge oscillations in coupled quantum wells
Phys Rev B57 (16) R9443-6 (1998)

J Barnes, E S-M Tsui, K W J Barnham, S C Macfarlane, C Button, J S Roberts,
Steady state photocurrent and photoluminescence from single quantum wells as a function of temperature and bias
J Appl Phys 81, (1997), 892-900

K W J Barnham, I Ballard, J Barnes, J Connolly, P Griffin, B Kluftinger, J Nelson, E Tsui, A Zachariou
Quantum Well Solar Cells
Applied Surface Science, 113/114, (1997), 722-733

P Griffin, I Ballard, K W J Barnham, J Nelson, A Zachariou, C Button, M Hopkinson, M A Pate
Advantages of Quantum Well Solar Cells for TPV
Proc Third NREL Conf on Thermophotovoltaic Generation of Electricity (1997), 411-421

P Griffin, I Ballard, K W J Barnham, J Nelson, A Zachariou, J Epler, G Hill, C Button, M A Pate
The application of quantum well solar cells to thermophotovoltaics
Solar Energy Materials and Solar Cells 50, (1997), 213-219

P R Griffin, J Barnes, K W J Barnham, I Ballard, M Cabodi, M Mazzer, J S Roberts, R Grey, G Hill, M A Pate, A Marti, J C Maroto, R F Reyna, L Cuadra, M Yang, M Yamaguchi
A method for optimising strained GaAs/InGaAs quantum well solar cells and preliminary results under concentration
Proc 14th European Photovoltaic Solar Energy Conf, Barcelona, (1997), 1732-1735

X Huang, A J Seeds, J S Roberts
Reverse bias tuned multiple quantum well ridge guide laser with uniform modulation response
Appl Phys Lett, pp 765-766, 71(6), 1997

P G Huggard, J A Cluff, C J Shaw, S R Andrews, E H Linfield, D A Richie
Coherent control of cyclotron emission from a semiconductor using sub-picosecond electric field transients
Appl Phys Lett 71 (18) 2647-2649 (1997)

P G Huggard, C J Shaw, J A Cluff, S R Andrews, R Grey
THz magneto-optics of coupled quantum wells
Physica Status Solidi A 164, 561-566 (1977)

P G Huggard, J A Cluff, C J Shaw, S R Andrews
Polarisation dependent efficiency of photoconducting THz transmitters and receivers
Appl Phys Lett 72 (17) (1998)

J Nelson, I Ballard, J Barnes, N Ekins-Daukes, K W J Barnham, B Kluftinger, E S M Tsui, C T Foxon, T S Cheng, J S Roberts
Reduced radiative currents from GaAs/InGaAs and AlGaAs/GaAs p-i-n quantum well devices
Conf Record of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, (1997), 919-922

J Nelson, J Barnes, K W J Barnham, N Ekins-Daukes, B Kluftinger, E S M Tsui, C T Foxon, T S Cheng, J S Roberts
Radiative Currents from GaAs/InGaAs and AlGaAs/GaAs Quantum Well Solar Cells
Proc 14th European Photovoltaic Solar Energy Conf, Barcelona, (1997), 1716-1719

J Nelson, J Barnes, N Ekins-Daukes, B Kluftinger, E Tsui, K W J Barnham, C T Foxon, J S Roberts
Observation of suppressed radiative recombination in single quantum well p-i-n photodiodes

J Appl Phys, 82, (1997), 6240-6246
A Syahriar, R R A Syms, T J Tate
Thermo-optic switches fabricated by electron beam irradiation of silica-on-silicon
IEEE J Lightwave Tech LT-16, 841-846 (1998)

R R A Syms
Electrothermal frequency tuning of folded and coupled vibrating micromechanical resonators
IEEE/ASME J Microelectromech Syst 7, 164-171 (1998)

R R A Syms
Rotational self-assembly of complex microstructures by the surface tension of glass
Sensors and Actuators A65, 238-243 (1998)

R R A Syms, V M Schneider, W Huang, M M Ahmad
High-on silica-on-silicon channel waveguides based on sol-gel germanophosphosilicate glass
Elect Lett 33, 1216-1217 (1997)

R R A Syms, A S Holmes, W Huang, V M Schneider, M Green
Development of the SC-RTA process for fabrication of sol-gel based silica-on-silicon integrated optic components
9th Int Workshop on Glasses, Ceramics, Hybrids and Nanocomposites from Gels, August 1997

R R A Syms, E M Yeatman, A S Holmes
Research activities on microengineering at Imperial College
Micromachine 22, 4-5 (1998)

S Taylor, J J Tunstall, T J Tate, R R A Syms, M M Ahmad
Silicon micromachined mass filter for a low power, low cost quadrupole mass spectrometer
Proc 1998 IEEE Int Workshop on MicroElectroMechanical Systems, Heidelberg, Germany, 25-29 January, pp 8-442 (1998)

S Taylor, J J Tunstall, R R A Syms, T J Tate, M M Ahmad
Initial results for a quadrupole mass spectrometer with a silicon micromachined mass filter
Elect Lett 34, 546-547 (1998)

G Thucydides, J M Barnes, E S-M Tsui, K W J Barnham, C C Phillips, T S Cheng, C T Foxon
Tailored carrier escape rates in GaAs/$Al_{10.3}Ga_{0.7}$As asymmetric double quantum wells Semicond Sci Technol 12, (1997), 35-41

A Zachariou, J Barnes, K W J Barnham, J Nelson, E S M Tsui, J Epler, M Pate
A carrier escape study from InP/InGaAs Single Quantum Well Solar Cells
J Appl Phys, 83, (1998), 877-881

Appendix III

Publications by CMF Staff and Collaborators

The names of CMF staff are printed in italics

G Arthur, B Martin, N Eilbeck, C A Mack
Analysing the Dissolution Characteristics of Deep UV Chemically Amplified Photoresist
Micro- and Nano-Engineering 1997

G Arthur, B Martin
Simulation of Optical Lithography in the Deep UV
ECOLE Forum on Deep UV Lithography, Leuven, Belgium, 7-8 October 1997

G Arthur, C A Mack, B Martin
A New Development Model for Lithography Simulation
Olin Microlithography Seminar, Interface 1997

G Arthur, C Wallace, B Martin
A Comparison of Recent Development Models in Optical Lithography Simulation
IC Metrology, Inspection and Process Control XII, SPIE, 1998

G Arthur, B Martin
A novel method of optical proximity correction using antireflective layers and individual photoresist characteristics
Microelectronic Engineering 1997, Vol 35, No 1-4, pp 185-188

G Arthur, N Eilbeck, B Martin
Effect of temperature variations in the post-exposure processes of optical lithography
Microelectronic Engineering, 1997, Vol 35, No 1-4, pp 137-140

C Caliendo, P Verardi, E Verona, A D'Amico, C DiNatale, G Saggio, M Serafini, R Paolesse, *S E Huq*
Advances in SAW-based gas sensors
Smart Materials & Structures, 1997, Vol 6, No 6, pp 689-699

Z Cui
Monte carlo simulation of electron beam lithography on topographical substrates
Microelectronic Engineering, Vol 41/42 (1998)

Z Cui
Simulation of micro-strip deflectors for field emission display
Charged Particle Optics III, SPIE Vol 3155 (1977)

Z Cui, P D Prewett
Proximity correction of chemically amplified resists for electron beam lithography
Microelectronic Engineering, Vol 41/42 (1998)

Z Cui, P D Prewett
ESPRIT 'NANCAR' Project - Second Year Technical Report (1998)

Z Cui, P D Prewett, J G Watson
Focused ion beam biased repair of conventional and phase shift masks
Journal of Vacuum Science & Technology B, 1996, Vol 14, No 6, pp 3942-3946

Z Cui, R A Lawes
Low cost fabrication of micromechanical systems
Microelectronic Engineering, 1997, Vol 35, No 1-4, pp 389-392

Z Cui, R A Moody, I M Loader, J G Watson, P D Prewett
Optimized process for electron beam nanolithography using AZPN114 chemically amplified resist
Microelectronic Engineering, 1997, Vol 35, No 1-4, pp 145-148

Z Cui, R A Lawes
A new sacrificial layer process for the fabrication of micromechanical systems
Journal of Micromechanics and Microengineering, 1997, Vol 7, No 3, pp 128-130

R R Dammel, J Sagan, E Kodindia, C A Mack, *G Arthur,* C Henderson, C G Willson
Improved Simulation of Advanced Resist Materials Using New Development Models
Advances in Resist Technology and Processing XV, SPIE, 1998

N Glezos, G P Patsis, *Z Cui*
E-beam proximity correction for negative tone chemically amplified resists taking into account post-bake effects
Microelectronic Engineering, Vol 41/42 (1998)

G H Grayer, *S E Huq, Z Cui, P D Prewett*
The planar field-emitting deflectron as logic element and amplifier
Tech Digest of the 10th International Vacuum Microelectronics Conference, Korea, 1997, pp 206-208

M Huang, *S E Huq, P D Prewett,* G W Smith, P R Wilshaw
Anodisation of griddded silicon field emitter array
Tech Digest of the 10th International Vacuum Microelectronics Conference, Korea, 1997, pp 87-91

S E Huq, G H Grayer, *P D Prewett*
Comparative study of gated single crystal silicon and polysilicon field emitters
Journal of Vacuum Science & Technology B, 1997, Vol 15, No 6, pp 2855-2858

S E Huq, G H Grayer, S W Moon, *P D Prewett*
Fabrication and characterisation of ultra sharp silicon field emitters
Materials Science and Engineering B - Solid State Materials for Advanced Technology, 1998, Vol 51, No 1-3, pp 150-153

S E Huq, M Huang, P R Wilshaw, *P D Prewett*
Microfabrication and characterisation of gridded polycrystalline silicon field emitter devices
J Vac Sci Tchnol B 16(2), pp 796-798, 1998

Jing-lei Du, Yong-kang Guo, *Z Cui*
A new method for optical proximity correction
Applied Lasers, Vol 17 (6), 1997 (in Chinese)

R G Jones, B R Penfold, G Cordina, *B H Bracher*
Electron beam resists based on copolymers of dimethylstyrene & vinyl benzene chloride synthesised by living free radical polymerisation
3rd Int Symposium on Materials Chemistry, Exeter, July 1997

A J Kent, A J Naylor, P Hawker, M Henini, *B H Bracher*
Observation of giant oscillations in the phonon-induced conductivity of a GaAs quantum wire
Phys Rev B - Condensed Matter, Vol 55, No 15, pp 9775-9778 (1997)

V A Kudryashov, V V Krasnov, *P D Prewett,* T J Hall
Process latitude enhancement for 3d structure formation in e-beam lithography
Microelectronic Engineering, 1997, Vol 35, No 1-4, pp 487-490

V A Kudryashov, V V Krasnov, *P D Prewett,* T J Hall
Low energy electron beam lithography: pattern distortion by charge trapped in the resist
Microelectronic Engineering, 1997, Vol 35, No 1-4, pp 165-168

R A Lawes
Microengineering Technologies and how to exploit them
IEE Colloquium on Microsystems Technology, 8 April 1997

R A Lawes
Microsystems Engineering
Visions of Tomorrow, 150th Anniversary Symposium, Institution of Mechanical Engineers, 75-81 (1997)

B Martin, *G Arthur,* C Brown
Process Control of Contact Holes for Sub-half-Micron CMOS Technology
Micro- and Nano-Engineering 1997

B Martin, *G Arthur,* C Wallace
Influence of Lens Aberrations on High Resolution Imaging using Low Reflectivity Substrates
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