COOP-CT-2006-032732

MONARCH

Ultra-bright nanoscale SEM-on-a-chip

Co-operative Research Project

Sixth Framework Programme, Horizontal Research Activities Involving SMEs

Final activity report

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Project co-ordinator name:	Dr. Bruce R. Napier
Project co-ordinator organisation name:	Vivid Components Ltd.
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PUBLISHABLE EXECUTIVE SUMMARY

PROJECT AIMS AND OBJECTIVES

The MONARCH project made significant progress towards the world's first scanning electron microscope (SEM) on-a-chip. Such an instrument would represent a step-change in electron beam (e-beam) technology comparable with the introduction of the silicon chip to electronics. This device will be orders of magnitude smaller than existing technology, operate at lower voltages and have an order of magnitude higher resolution for a fraction of the cost of a current state-of-the-art SEM. It would provide the first instrument capable of rapidly scanning a surface layer and producing an image with elemental identification at atomic resolution. This disruptive technology has dramatic implications for many sectors other than electron microscopy, including e-beam lithography, genetic sequencing, ultra-high density data storage and focussed ion beam milling. In particular it is expected to be a key enabling tool for the booming sectors of nanotechnology and MNEMS (micro-nano-electromechanical systems). Crucially it could also allow lithography on a scale suitable for true nano-electronics.

The physics behind the MONARCH project are beautifully simple: by scaling the device dimensions down to the nano-scale, the voltages, beam energies and aberrations are scaled down proportionally. The system becomes diffraction-limited, rather than aberration-limited, and the lenses can be electrostatic rather than magnetic. These principles have been known for decades, but the realisation of such devices has only been made possible through very recent parallel advances in several nano-machining technologies: improved FIB techniques, the evolution of MEMS technology and scanning probe microscopy (*e.g.* very short focal length electrostatic lenses). In short these techniques have transformed a thought-experiment into a realistic possibility: ultra-low energy, ultra-high power, ultra-pure e-beams.

PROJECT CO-ORDINATOR

This ambitious co-operative research project is being part financed by the European Commission's Sixth Framework Programme, under contract number COOP-CT-2004-032732. The co-ordinating organisation is the SME, Vivid Components Ltd; the project coordinator is Dr. Bruce Napier: bruce@vividcomponents.co.uk

THE PARTNERSHIP

The partners in the consortium are listed in the table below, with a brief description of their role in the project.

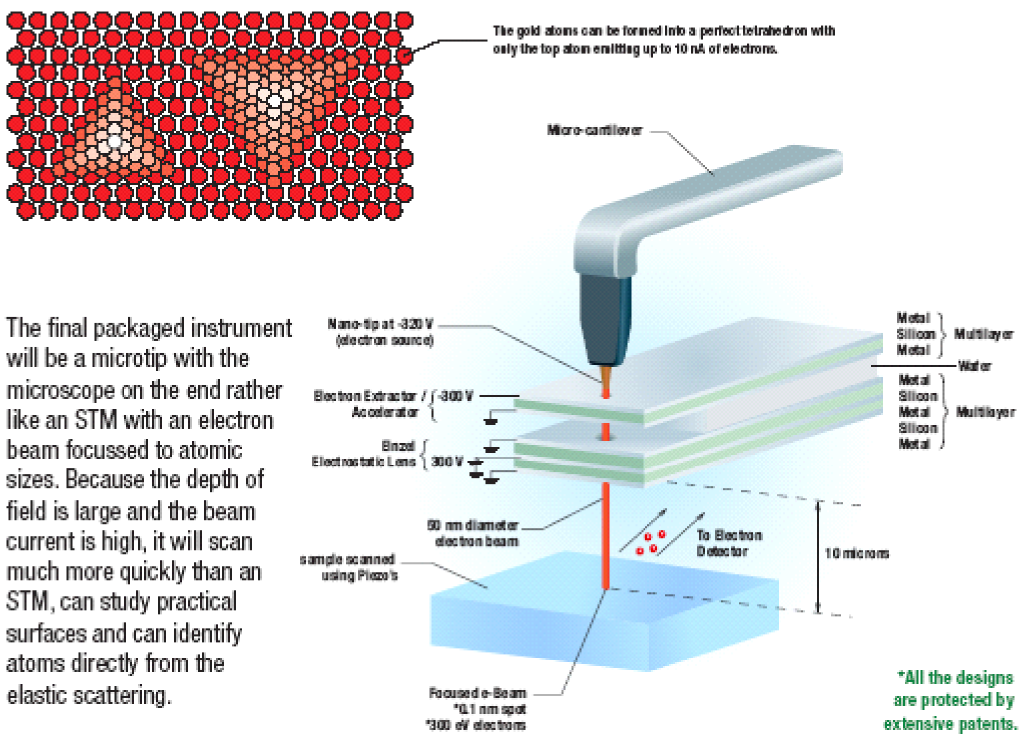
Name	Role in project
Vivid Components Ltd.	Project management and administration
Nanofactory Instruments AB	Integration of SEM-on-a-chip system
NFAB Ltd.	Functional design of SEM on a chip; leader of dissemination activities
Concept to Volume B.V.	Design and design-for-manufacture of the chip body using Micro System Technology (MST)
OMICRON NanoTechnology GmbH	End user
Roper Industries Ltd.	End user
University of Salford	FIB milling to manufacture nano-scale parts of the microscope; testing of SEM-on-a-chip
MESA+ (University of Twente)	Micro-scale manufacturing of chip body; FIB processing; MEMS processing
University of Chalmers	Adaptation and integration of detector for SEM-on-a-chip operation

RESULTS ACHIEVED

The Monarch project investigated a sub-miniature scanning electron microscope: a completely new concept in electron microscopy. The microscope is 5µm long and has atomic resolution (2 Å) at 500 eV energy and 10 nA of current. The low energy would mean it could identify single atoms on a surface as well as being able to make holograms of large molecules.

- Magnification is 1µm and the focal length is 7µm
- Aberrations contribute less than 0.2Å to the spot size

The illustration below describes the device operation.



PROJECT WEB SITE

The project website is www.monarchproject.org

This includes contact details, a consortium description, a downloadable summary of the project results and other links to related articles.

1: PROJECT OBJECTIVES AND MAJOR ACHIEVEMENTS DURING THE REPORTING PERIOD

OVERVIEW OF PROJECT OBJECTIVES AND RELATION TO STATE OF THE ART

Project overview

The research approach of the MONARCH project (SEM-on-a-chip) recognises that such a system requires activity in three distinct regimes:

1) Nano-scale: *e.g.* the nanotip and the aperture through the SEM element
2) Micro-scale: *e.g.* the chip body components, detector and manipulator device
3) Macro-scale : *e.g.* the UHV system, user interface.

A major challenge for MONARCH project was to interface effectively between these regimes. For this reason the MONARCH project addressed the following subjects in its four technical WPs:

- Production of micro-machined SEM-on-a-chip bodies (WP1)
- Processing of chip bodies to form functional SEM-on-a-chip devices (WP2)
- Modification & integration of e- detector for SEM-on-a-chip operation (WP3)
- Integration of SEM-on-a-chip with e- detector in UHV system (WP4).

The project had the following key objectives in this period:

-Manufacture of stable emission from nano-tips with atomic dimensions: This was achieved using several tip fabrication methods, and found a new method of tip production.

-Construction of an ultra-high brightness electron source: This was addressed in several ways, including planar FIB milling and drilling using a self generated field ionised beam or direct drilling, using a FIB of a multilayer.

-A low voltage focused beam of electrons in the energy range 0.1-3.0keV: This is made by attaching a lens (or lenses) to the source at a short distance from the source and making the final focal length less than 10μm. The final impact of the instrument will depend on the measured performance. A rough guide is:

- Resolution ≥1nm. This will have the lowest financial impact but still produce a reasonable level of wealth creation
- Resolution in range 0.2 - 1nm. Large financial impact
- Resolution 0.1nm, coupled with element sensitivity. Massive financial impact particularly if it can be developed to sequence DNA.

The following radical innovations beyond the current state-of-the-art were targeted:

- SEM on a chip – vastly smaller than current dimensions
- Resolution of 0.1 nm (1 Å), a factor of 10 better than the best large commercial instruments.
- The electron source is 10,000 times brighter than existing ones
- Production costs are a fraction of those for existing instruments
- Simple market entry possible as an add-on to all existing near field instruments such as scanning tunnelling microscopes (STMs) and atomic force microscopes (AFMs)
- Can be readily modified to other applications: focused ion beam machines (FIBs), lithography systems, magnetic imaging microscopes and read/write systems.
- Rapid scanning – able to see individual atoms and identify them chemically a million times faster than chemical imaging techniques
- Large depth of field, unlike near field probes – rapid scanning of surfaces of nanodevices and nanosystems.

SUMMARY OF RECOMMENDATIONS FROM PREVIOUS REVIEWS

There were five recommendations from the first reporting period review. There follows a list of the recommendations, with the actions taken to address them:

1.) Confirm conclusion of the Consortium Agreement
-The Consortium Agreement had in fact been signed by the whole consortium before the project start. A pdf of the signed version was put on the project website and sent to the Project Officer (D1).

2.) Provide better justification of the over spending by MESA+ and plan resource re-allocation accordingly.
-It was expected that the spend by MESA+ was weighted more in the first year because the work carried out related almost entirely to the chip bodies, and not the application of the bodies in the latter stages of the project. A budget assessment was carried out and it was forecast that MESA+ spend was on target due to much reduced work in the second period. In fact the Yr 2 MESA+ claim was small, but there was a total overspend of 8.5%; it was emphasised to MESA+ throughout that costs incurred over their budget may not be reimbursed.

3.) Ensure Vivid's project management resources are budgeted correctly.
-In the project extension and review of the budget and Description of Work (Amendment 1; Oct-08), Vivid's role was extended to include considerable scientific coordination (RTD activity) to manage the complex mitigation activities for the chip bodies, aperture formation and nano-tip manufacturing work. This also included a review of the coordination management for the extended project period (MAN activity; 100% funded).

4.) Confirm the ongoing commitment of OMICRON, Roper and NFAB at the next project management meeting or reallocate their work accordingly.
-Both the end users, Omicron and Roper, did not receive any funding (even travel), but they continued to participate in project meetings and provided useful commercial perspective. The interest of NFAB was never in any doubt; it was the project instigator and technical lead, and continues to work towards the Monarch objectives (now outside the funded framework of the project).

5.) Ensure that dissemination and use aspects are addressed adequately through provision of a detailed plan, public access to website, confirmation and resolution of confidentiality issues and timely planning of workshops.
-Dissemination activity was thoroughly planned and formed a major part of the work in the second period. The public website was extended, including downloadable summaries of project progress. Confidentiality remained important, since the project did not wish to reveal incomplete work; however the newsletters gave a good description of the exciting progress made in the project. Regarding the workshops; it was agreed with the project officer (May-09) that an extensive array of other activity would be a better use of dissemination resource, since the results from the intense project activity were not at an appropriate stage for a workshop. Therefore a range of other activities were undertaken to disseminate the project results. Twenty items are described in the PUDK (see Annex 1) including trade shows, TV articles, videos, trade press articles, wider media articles, conference presentations, academic journal publications, Monarch presentations at other appropriate workshops and items on in-house websites.

OBJECTIVES FOR THE REPORTING PERIOD, WORK PERFORMED AND MAIN ACHIEVEMENTS

The main objectives for the project were as follows:

1.) Project launch
2.) Establish MONARCH web site (D4)
3.) Initial design of the chip body (D2)
4.) Begin annular detector selection and modification (D13)
5.) Project web site maintenance
6.) Final chip body design (D30)
7.) Fabrication of micro-machined chip bodies (D12)
8.) Fabrication of UHV system (D11)
9.) Operational integrated detector (D13)
10.) FIB widening process definition (D14)
11.) Manufacture of nano-tips for demonstrator (D15)
12.) Apertures formed on chips for demonstrator (D16)
13.) Manufacture and integration of nanopositioning system (D19)
14.) Manufacture of chip bodies for demonstrator (D12)
15.) Optimised detector & SEM-on-a-chip operational (D22 & D23).

Objective 1: Project launch
The project was successfully launched at the kick-off meeting in Amsterdam. The consortium agreement was signed by all partners. Successful research links were established between the partners, which have been maintained throughout the first project year through further plenary meetings in Sweden (Month 6) and London (Month 9), as well as through technical meetings and other correspondence. There has been excellent cooperation between the partners, and agreement that the skill sets of the partners are well aligned and complementary.

Objective 2: Establish MONARCH web site (See D4)
The website was live by Month 3 (www.monarchproject.org) (D4). It was decided to keep the public aspects of the project very limited until appropriate IP protection is in place. The members area is password protected, and contains up-to-date information on the project progress, actions, deliverables, news and events. A blog was also established, at the request of the consortium, at: www.monarchproject.wordpress.com. This is a secure "members only" site.

Objective 3: Initial design of the chip body (See D2)
The initial chip body design, based on a TEOS oxide substrate, was circulated for comment to the consortium in Month 5 (D2). Based on this design a series of "short loop tests" were designed and carried out to ensure the performance of the chip was adequate for the application. These tests did uncover weaknesses in the design which were improved in the final version.

Objective 4: Annular detector selection and modification (see D13)
Based on the chip design development work, it was agreed at the 6M meeting that a slightly modified off-the-shelf detector (a single channel electron multiplier) could be used and the requirement to design a custom detector could be avoided. This freed resource for the UHV system modifications and nano-positioning work.

Objective 5: Project web site maintenance (see www.monarchproject.org)
The public area of the website was extended to include downloadable documents describing project progress. The password protected members area was kept up-to-date with information

on the project progress and news, a detailed actions register, deliverables, monthly progress reports for each WP and events. NB A secure "members only" blog was established, at the request of the consortium, at: www.monarchproject.wordpress.com but this was not found to be an effective tool in the Monarch project. Instead monthly reports were found to be a much more effective mechanism (see Task 5.1).

Objective 6: Final chip body design (see D30)
In the first reporting period, it was found that the TEOS oxide substrate of the initial chip body design exhibited a progressive stress creep which caused buckling of the material over a period of weeks or months. Furthermore, small fragments of substrate material from the "break grooves" were released into the chamber, and risked damage to the equipment. Therefore the final chip design (D30), developed by MESA+ and C2V, was based on a poly-silicon substrate with a modified break groove design. Test chips were built and tested. To save cost and time, these chips were "dummy" chips without the electrode structures in place. (The electrodes are based on well-understood standard technology and it was agreed that nothing would be gained by including them in the test structures.) Extensive testing on the D30 design showed excellent results.

As a mitigation route, several other chip body designs were developed in parallel with the main D7 solution. These options were developed as the theoretical modelling yielded other, simpler, solutions to the chip design:

- Horizontal silicon substrate design
- Vertical design based on silicon substrate; aluminium and silica electrodes
- Vertical design based on silicon substrate; tungsten and polyimide electrodes
- Simplified vertical design using tungsten and silica/SU photoresist electrodes.

Objective 7: Fabrication of micro-machined chip bodies (see D12)
The first samples were manufactured by Month 6 (M1). A set of TEOS samples were sent from MESA+ in Month 10 to several members of the consortium for testing. Samples of the alternative designs were also fabricated.

Objective 8: Fabrication of UHV system (see D11)
Existing UHV systems were successfully modified for Monarch purposes at Salford and Chalmers. This allowed parallel working by two groups conveniently located geographically: NFAB and Salford University (Manchester, UK) and Chalmers and Nanofactory (Gothenburg, Sweden). The two UHV systems had different characteristics to permit different, related experimentation. However, both successfully accommodated the Nanofactory nano-positioning apparatus.

Objective 9: Operational integrated detector (see D13)
Based on the chip design development work a modified off-the-shelf detector (a single channel electron multiplier) could be used and the requirement to design a custom detector could be avoided. This freed resource for the UHV system and nano-positioning work. The detector was purchased, modified and integrated successfully.

Objective 10: FIB widening process definition (see D14)
The FIB widening process was successfully identified by workers at Salford. The process was defined for the Salford apparatus, but may be easily adapted for other installations.

Objective 11: Manufacture of nano-tips for demonstrator (see D15)
Nano-tips were successfully fabricated using a several methods and a range of materials (including tungsten, carbon nanotubes, molybdenum, nickel *etc.*) were investigated by Salford and Chalmers. Of particular interest are:

- Two-dimensional in situ fabrication using FIB on tungsten (Salford)
- In-situ tungsten tip sharpening; this is a novel technique discovered at Chalmers during the Monarch work ("etch and stretch")
- Carbon nanotubes grown on a Pt/Ir wire (Chalmers).

Objective 12: Apertures formed on chips for demonstrator (see D16)
Apertures were successfully formed by both Chalmers and Salford throughout the second period. This included exploration of the ideal location for the apertures on the chip and optimising of process parameters.

Objective 13: Manufacture and integration of nano-positioning system (D19)
Nanofactory carried out first class work throughout the second period, working closely with both Chalmers and Salford. They successfully delivered and helped to integrate correctly operating nano-positioning systems and software interfaces to both locations, helped in the interpretation of results and provided guidance for optimum use of the impressive kit.

Objective 14: Manufacture of chip bodies for demonstrator (see D12)
The main D30 design trials were very successful and expectations were high approaching the final stages of the project, when the chips, tips, detector and nano-positioner could finally be brought together in the UHV system. However, critically there was a processing error in the final step of chip production which it was only possible to identify at this final stage (in the last two weeks of the project). This meant that the chip did not have the correct electrode structure to give lensing action, with very disappointing consequences for the final project output. An analysis of the processing error was carried out and it appears that a single step was missed resulting in the problem. This is discussed in the Appendix to D12.

For just such an eventuality, as a mitigation route, several other chip body designs had been developed in parallel with the main D30 solution. Despite this multi-fronted approach, each of these routes to working chips encountered problems, in each case NOT due to design flaws, but cost, commercial or processing reasons (see WP1).

Objective 15: Optimised detector & SEM-on-a-chip operational (D22 & D23)
The integrated system functioned and was tested successfully. All the individual elements are in place and operating. The Monarch tips were aligned (using the Monarch nano-positioning equipment) with apertures milled in Monarch chips using a Monarch-developed process, emitted a beam which was scanned and detected on the integrated Monarch detector inside the Monarch-adapted UHV systems. Very disappointingly, the lack of electrode structure on the chips (due to an error in a single processing step) meant that focusing of the beam could not be demonstrated within the project timescale. Work continues outside the project but cannot be reported here.

PROBLEMS ENCOUNTERED AND SOLUTIONS

Excellent progress was made throughout the project. The consortium has worked well together throughout the project, and built up strong and effective working relationships. No contractor's performance has given rise to any concern. This teamwork was effective in addressing some of the technical challenges.

i.) First reporting period

Some potential problems were apparent at the end of the first reporting period, and mitigating actions were taken. Due to the intensely parallel and dynamic nature of the work, it was decided that an additional coordination meeting in Month 9 was necessary, and this was extremely useful in coordinating the work.

Chips: The initial MESA+ chip design did exhibit some problems, but this was not unexpected, and the final design seemed to have solved all the observed difficulties. Since problems would not be apparent until the very end of the project, it was decided to pursue other chip designs in parallel as mitigation options (see below).

Tips: Several new options for tip manufacture were uncovered during the first period, and it was decided to explore several of these, including material choice, at both Chalmers and Salford.

ii.) Second reporting period

Due to the parallel and fast-moving nature of the work, technical meetings were held quarterly after the 18M review (Chalmers): productive and effective meetings were held at 21M (Rome), 24M (Chalmers), 27M (Salford), and 30M (Chalmers).

Lack of electrode structure on MESA+ chip

With one unfortunate exception, all the elements of the project have been successful. However, very disappointingly, due to an error in a single processing step of the chip body build, there was not a functioning electrode structure on the chips. It was only possible to find this problem at the very end of the integration process (two weeks before the project end date). This meant that focusing of the beam could not be demonstrated within the project timescale. Work continues outside the project but cannot be reported here. Due to these chip problems, the final objective of a fully functioning SEM-on-a-chip was not achieved, and the dissemination of results must be limited until this work is completed.

Mitigation design chip problems

Because an operating chip was essential for the microscope operation, several parallel chip designs were pursued. Unfortunately each of the four back-up chip designs encountered problems. However, it is emphasised that these reflect the practical difficulties of operating in this new research field, and certainly do not represent any concerns over the principle of the SEM-on-a-chip or indeed the individual chip designs. The four designs, developed with the help of discussions with external groups reached the following conclusions:

- Horizontal silicon substrate design (Edinburgh SMC)
    - Processing problems led to poor layers: insufficient time to perfect process
- Vertical design based on silicon substrate; aluminium and silica electrodes (Edinburgh SMC)
    - Processing problems led to poor layers: insufficient time to perfect process

- Vertical design based on silicon substrate; tungsten and polyimide electrodes (Kelvin Nanotechnology; Glasgow, UK)
  - This option proved to be too expensive to pursue
- Simplified vertical design using tungsten and silica/SU photoresist electrodes (Cambridge Nanoscience Centre)
  - Whilst this looked the most promising solution of all, there were changes to the structure of the Centre and the staff involved left the facility. The chips were almost complete, but despite intense negotiations they would not be released.

2: WORK PACKAGE PROGRESS OF THE PERIOD

WORK PACKAGE 1 – CHIP BODY FABRICATION

Work package objectives

- Design chip body
- Identify chip body manufacture process
- Production of chip bodies for WP2

WP1 is the keystone of the technical programme. The chip body will be designed and built, which includes both features on the micro-scale and connections to the outside world. The deliverables include the final chip body design, process definitions and the supply of chip bodies to WP2.

Period 1: Progress towards objectives

Task 1.1 Chip body design process

The Monarch concept is to reduce the scale of the SEM by a factor of one million by using the latest MEMS technology. In a first approach and as a proof-of-principle, the SEM microchip, with a nano-sized hole in its centre, is mounted into a commercial STM instrument and then the sample is scanned using its piezotube in order to align the STM tip with the nano-hole to within a few nanometers (Figure 1). After this calibration, the electron beam should have a focusing point enabling atomic scan resolution. The design of the micro-SEM is chosen in such a way that only minor changes, if any, to the STM are required, as described in the following sections.

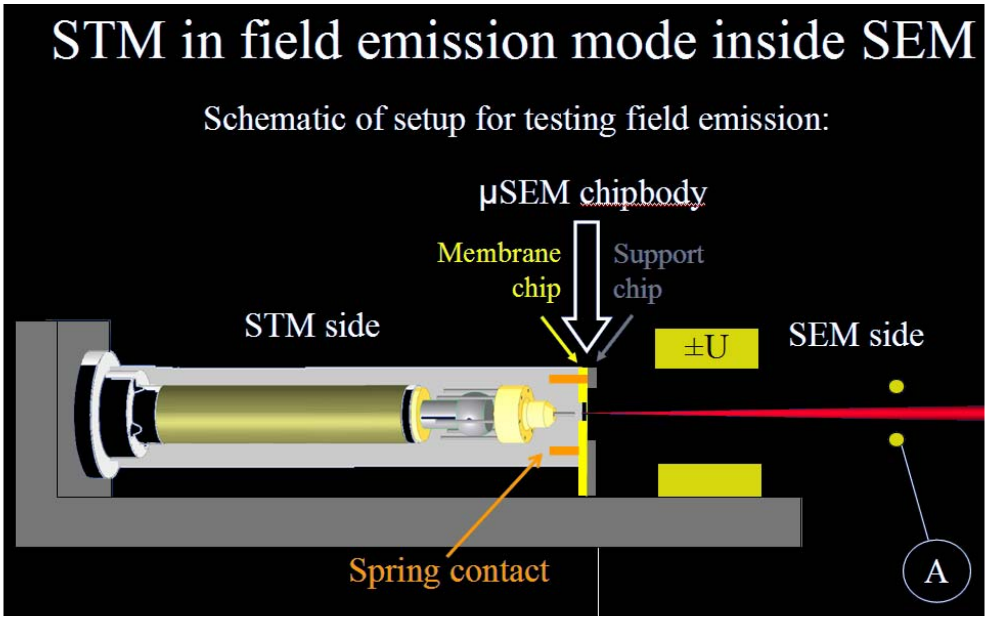


Figure 1 Schematic of the microSEM using an STM instrument

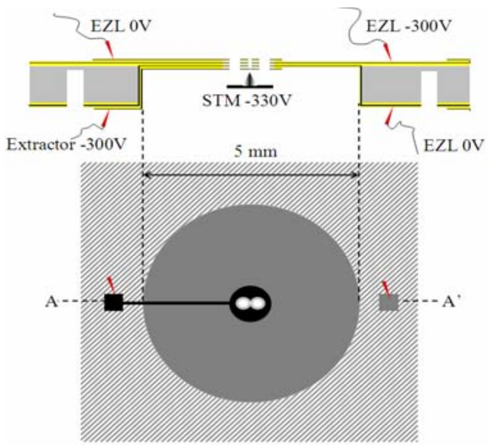


Figure 2 Cross sectional and top view of the membrane chip.

The design of the µSEM chip body is fairly simple; a silicon wafer, used as a supporting structure of the SEM membrane, is machined using standard photolithography in such a way that a thin membrane is spanning a centre hole of a few mm inside the silicon frame and forming the so-called membrane chip. The membrane chip incorporates all the necessary layers for the micro-SEM to operate correctly, *i.e.* including an electrode to extract electrons from the STM tip, electrostatic Einzel lens (EZL) electrodes to focus the beam, and insulating material between the conducting electrodes to prevent shorts Figure 2). Additionally, the centre of the membrane is machined with a focused ion beam (FIB) to create a tiny hole through the whole stack of layers in order to enable electron beam extraction and focusing. This hole is the most critical part of the micro-SEM. Because the most straightforward MEMS technology creates contact paths at both sides of the wafer and the STM "likes" the contacts to be at the same side, an extra support chip is used to achieve single side contacts.

The outcome of the theoretical analysis shows that a voltage of 300V across a 1µm thick insulating layer of is quite necessary for micro-SEM operation. This value is quite high for most insulating material and, so, special attention is paid to prevent breakdown. Moreover, due to the stacking of many layers, mechanical integrity of the membrane is found an important issue. In MEMS technology, a complete "manufacturing design" is defined, known as the process flow. In order to prevent any major flaw in the final process flow, critical parts such as the mechanical integrity are singled out beforehand and tested; the so-called short loop tests. For instance, the testing of dielectric strength of the insulating material can be tested in a simple system without the need for complete micro-SEM manufacturing. In this way major road blocks are foreseen and countered in time to prevent delay. In fact, the consortium is constructed in such a way, MESA+ (research) is working ahead of C2V (actual manufacturing) to pave the way for the micro-SEM fabrication.

The actual manufacturing of the membrane chip starts with a 1um thick insulating TEOS layer. The following layers of poly-silicon and TEOS are deposited on top of this layer using standard MEMS technology. Figure 3 shows a detailed schematic of the complete micro-SEM chip body that will be manufactured for the Monarch project. The chip incorporates test options for all the electrical connections on the chip to ease failure analysis in case of device malfunction. The critical steps in the process flow for the chip depicted in Figure 3, (used to define the short-loop tests) are described below:

1. Membrane strength: will the 1µm thin membrane (spanning several mm) survive fabrication?
2. Dielectric strength: can the insulating material maintain the high voltage without breakdown?
3. TEOS stress: can the TEOS mechanical stress be made sufficiently low, and tensile, to prevent buckling?
4. TEOS membrane: can the initial layer be cleaned sufficiently to enable a smooth surfaces?
5. TEOS-poly-silicon sandwich: does the TEOS membrane survive the deposition of polySi and is it still smooth?
6. Brake groove: can in-situ chip separation grooves be incorporated in the process flow to prevent dirty dicing?

Figure 1.4: Result of short loop test 1.

7. FIB processing: are there any issues with respect to charging and drifting while processing the nano-hole with FIB?
8. Poly-silicon conductivity: is conductivity sufficiently high to guarantee the electrode is an equi-potential?
9. Stud-bump contact: is the electrical contact between the membrane and support chip correct?
10. Membrane lithography: can the membrane layers be shaped using lithography?

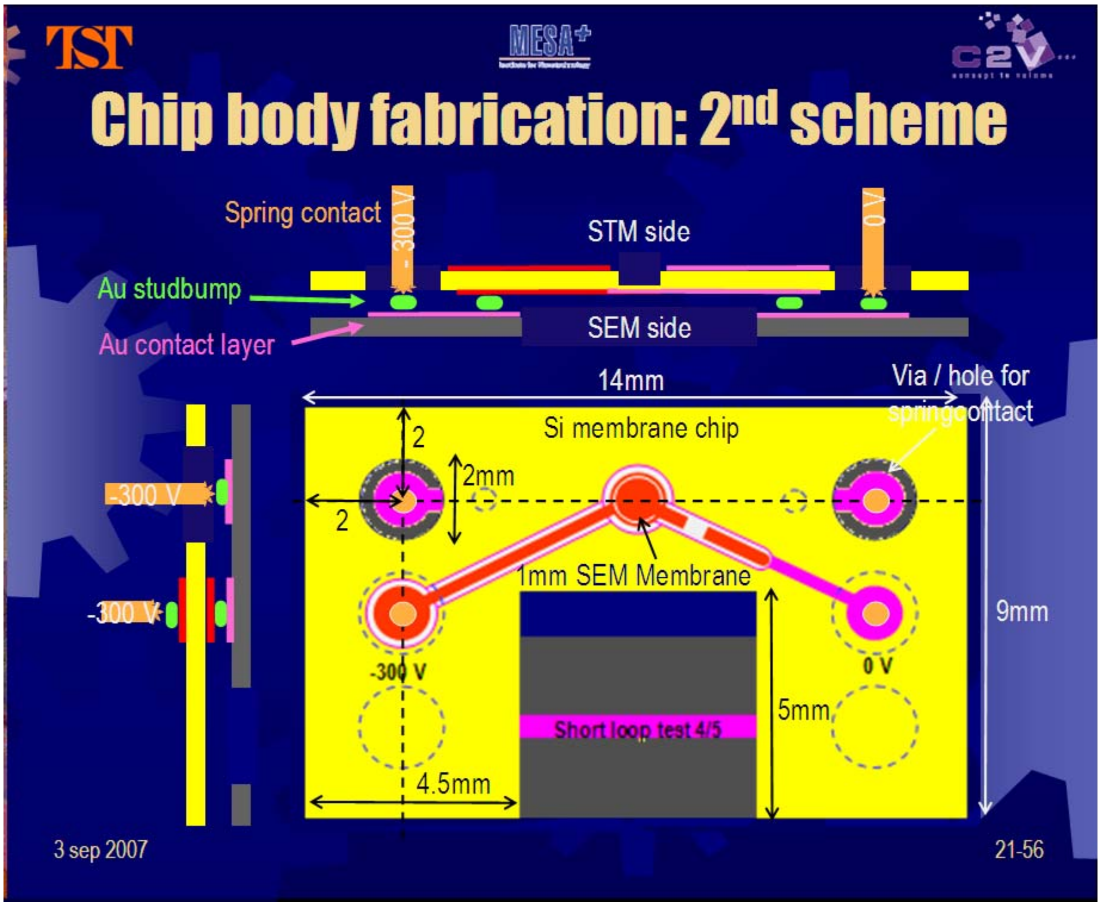


Figure 3: Cross-sectional and top view of the micro-SEM chip including contacting

Task 1.2 Chip body manufacture process

At the London meeting (Sep'07), the main process flow (design) for manufacturing the micro-SEM body was set. This flow describes a sandwich of TEOS oxide insulator material and semi-conducting poly-silicon. Although the dielectric and mechanical strength were studied and seemed satisfactory, ongoing tests were conducted. The results are presented next (the numbers indicate the short loop test number). After this some comments on the issue of polySi versus gold versus platinum will follow. In general, the main process flow was argued to be in good shape and no further road blocks were foreseen. Therefore, the final process would start by ordering the complete mask set and fabricating the microSEM body in January 2008.

1) Membrane strength: in the initial testing two different insulators were tested for their mechanical and electrical strength; TEOS oxide and silicon-rich (SiR) nitride. The as-deposited oxide showed buckling, which was caused by (minor) compressive stress. This effect is very disturbing because buckling promotes failure due to cracking. The nitride showed a perfect flat membrane due to the (major) tensile stress.

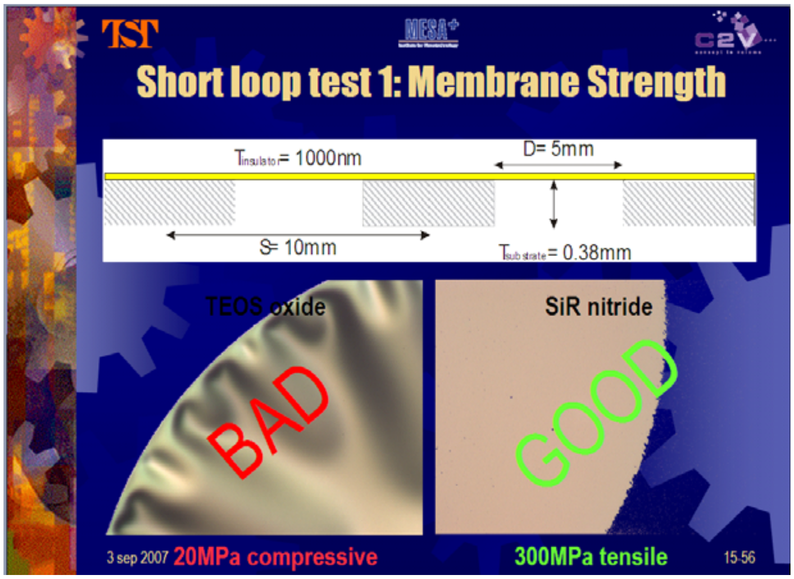


Figure 4: Result of short loop test 1.

2) Dielectric strength: in contrast to the former short loop test, the dielectric strength of the TEOS was found to be adequate whereas the nitride failed (in fact it was quite conductive).

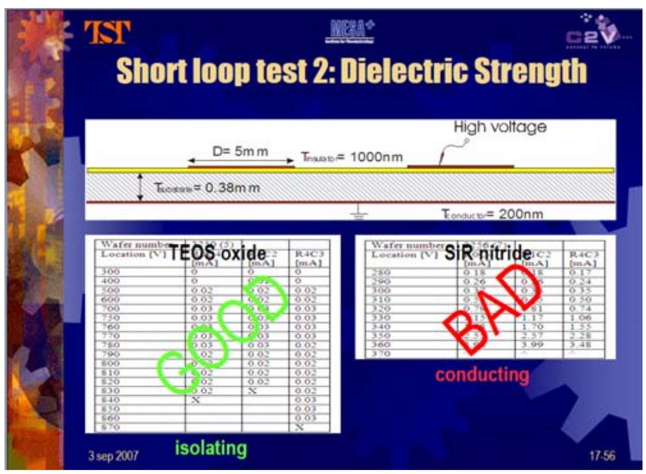


Figure 5: Result of short loop test 2.

3) The result of the initial short loop tests (1 and 2) showed that both oxide and nitride did not meet the target specification. It was argued that "repair" of the TEOS stress from compressive into tensile would be easier than preventing the nitride from its conducting property. It is well known that stress changes drastically after annealing due to densification and, indeed, the TEOS stress changed from slightly compressive into slightly tensile after 1hr anneal at 700°C. However, due to ageing effects, the stress changed back from tensile towards compressive after a few days. The

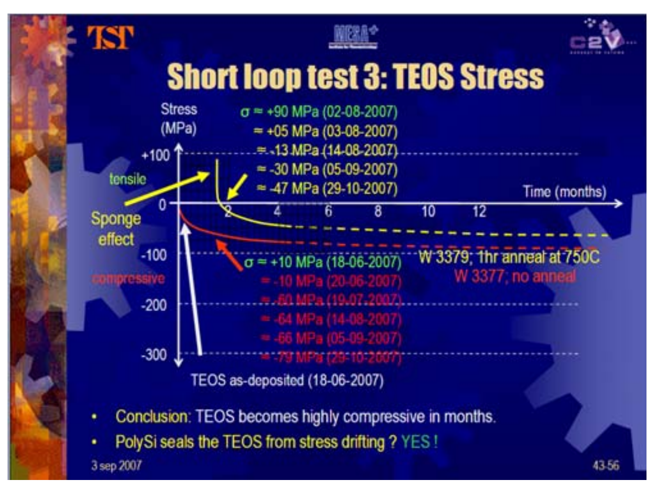


Figure 6: Result of short loop test 3.

problem has been mastered by a correct annealing step directly followed by the poly-silicon deposition. The membranes now have a slight and time-constant tensile stress.

4) During machining the center 1mm TEOS membrane (which will contain the nano aperture), it was found that etch debris caused by the etch process to shape the center hole was negatively affecting the smoothness of the polySi growth. The problem has been tackled by introducing a proper cleaning procedure to remove any residue from the etch process. The deposition of the polySi is now believed to be sufficiently smooth to enable SEM operation.

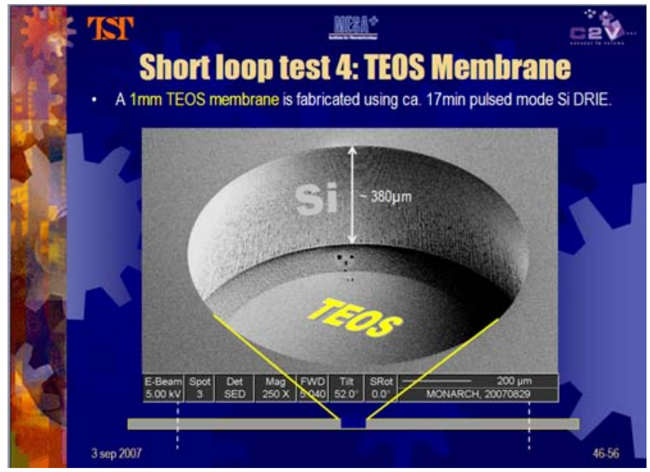


Figure 7: Result of short loop test 4.

5) When progressing in the main flow, an increasing number of layers will be stacked on top of a suspended membrane and potential problems were anticipated. However, testing showed that the whole stack could be fabricated without difficulty and the membrane strength is sufficient to survive processing steps such as wafer handling, spinning and cleaning.

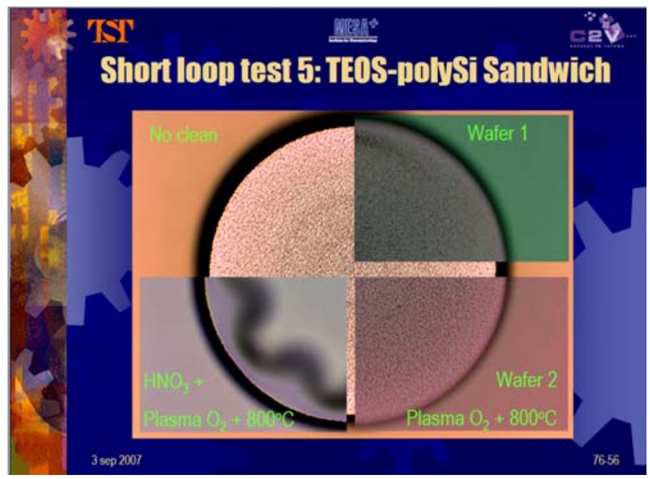


Figure 8: Result of short loop test 5.

6) Another potential problem uncovered in the initial tests was that during removal of the chips from the wafer by using "break grooves", some chips were already separate from the body of the wafer inside the etch equipment. The etch procedure has been adjusted and now the break groove system is working well.

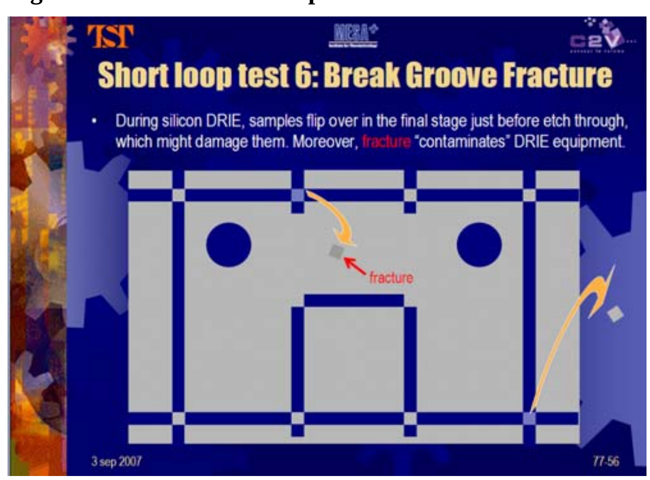


Figure 9: Result of short loop test 6.

7) Charging and drift problems were foreseen while FIBing the insulating TEOS layer inside the membrane. However, Nanofactory encountered no serious problems in their testing.

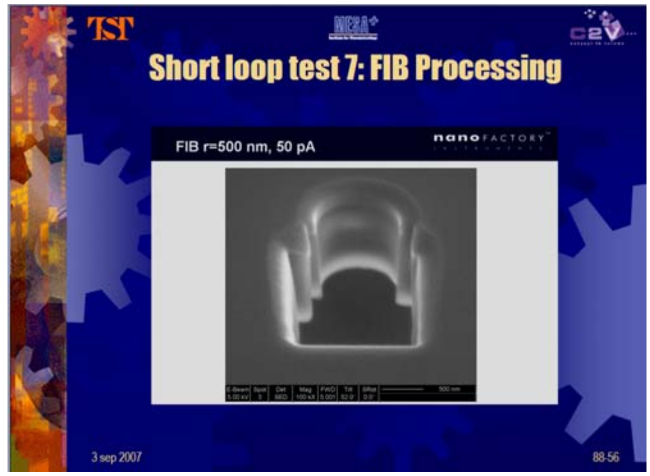


Figure 10: Result of short loop test 7.

8) It was anticipated by the partners that the limited conductivity of the polySi could inhibit correct functioning of the micro-SEM. This conductivity has been improved by a factor of at least 1000 by driving gold material into the polySi layers. The conductivity of a few Ohm*cm is believed to enable the high electric field to be available at the aperture.

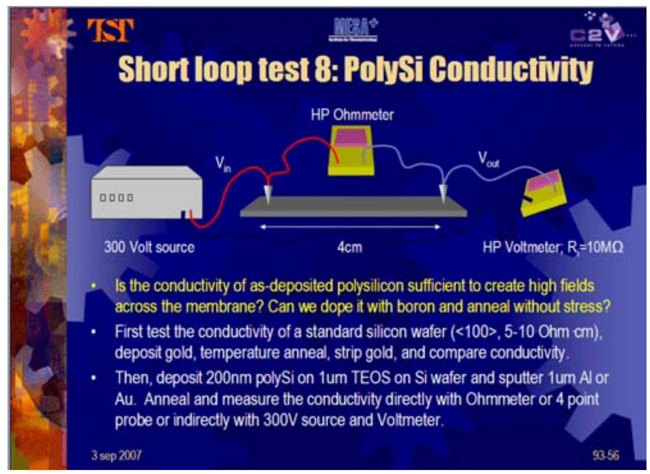


Figure 11: Result of short loop test 8.

9) The stud-bump contact between the SEM chip and support chip has not yet been tested, but the gold drive-in from the previous short loop (8) helps considerably, and it is expected that the change will be successful.

10) With respect to lithography, it was questionable if the fragile membrane would stand-up against the handling. By using a dry resist foil the problem seems to be overcome.

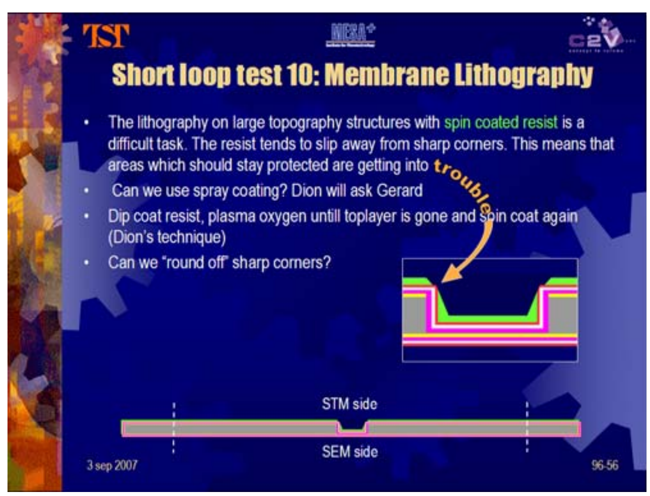


Figure 12: Result of short loop test 8.

Finally some remarks on the (semi-) conducting layer are presented:

1) The consortium agreed to follow the polySi chip body route. In this approach the final layer (*i.e.* the extraction electrode close to the STM tip) at both sides was still open to choice and could be polySi, gold, platinum, tungsten, molybdenum, or any other appropriate material.

2) If the approach in (1) caused major problems in device operation, an alternative route of stacked PECVD oxide and metal layers was to be followed. Some initial tests have been performed in this direction:
a) First of all, gold membranes were been sent to the partners for initial testing, as requested by the partners.
b) Secondly, a complete stack of four gold layers and five PECVD oxide layers were processed successfully as requested by the partners.

Parallel technique at University of Salford

Early in the project it was clear that there were two promising approaches to the chip body design. It was agreed for MESA+ to carry out their design, described in the previous sections, and for Salford to investigate an alternative ("back-up") design to be fabricated by their colleagues at Edinburgh University's SMC.

This base chip design has been through number iterations. The initial idea was to produce the structure by milling the aperture and tip from a uniform coating of tungsten. The problem with this concept was that it was not possible to produce electrical contact to the different elements. To overcome this problem it was decided to use standard micro-fabrication to place bond pads and connections to the elements that will be milled to form the tip and apertures. Simulation work showed that there a problem with this "flat" geometry: the Einzel lens geometry did not give the required beam profile. As a result the concept for the chip design was changed to one of a multilayer design. The layering scheme can be seen in Figure 13 and the contact layout can be seen in Figure 14. A base chip of this design allows for the use of both a CVD emission tip and STM style nano-positioned tip.

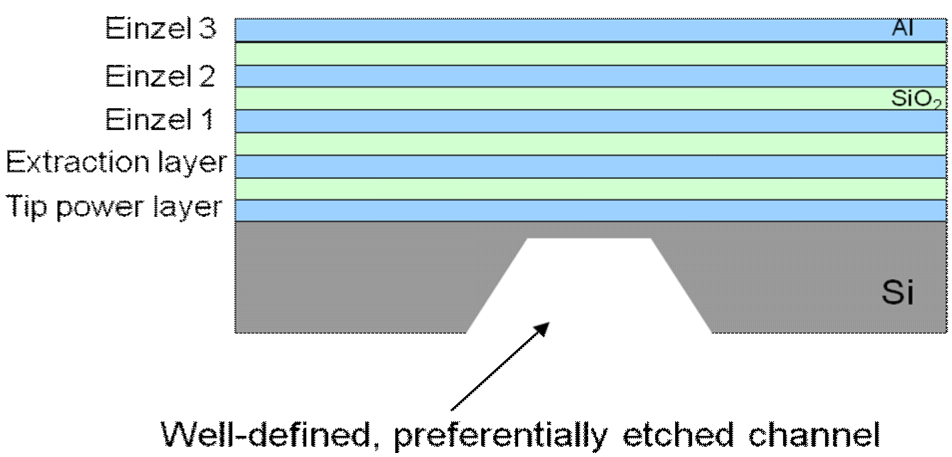


Figure 13 Sketch of the order of the multi-layer for the chip design.(Not to scale)

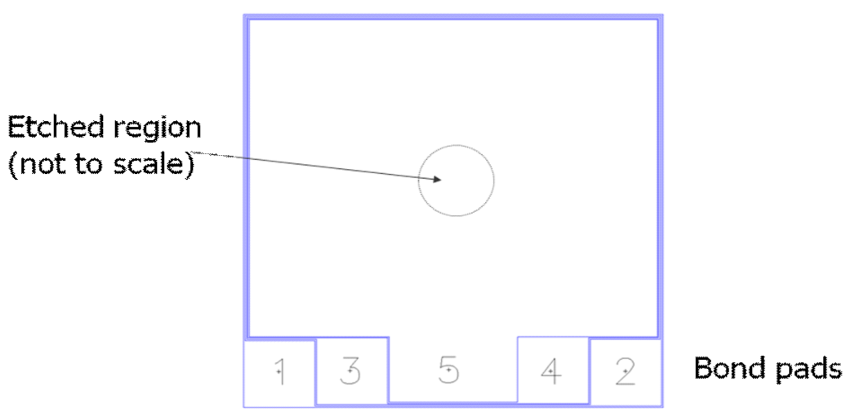


Figure 14 Plan view of the base chip.

Period 2 Progress towards objectives

Starting point of work at beginning of reporting period
-First samples of chip bodies built and tested at MESA+ and C2V. “Short loop tests” showed promising results
-Alternative design (as mitigation) based vertical electrode structure underway at Salford.

Task 1.1 Chip body design process

Changing of the device structure due to the short circuit of two electrodes (MESA+/ C2V)
At one of the test wafers, 200nm of gold was deposited and patterned (with 10nm Cr adhesive) at both sides of the μ-SEM membrane wafer.(the membrane stack consisting of a TEOS membrane + double side polySi + double side TEOS + double side polySi). A sketch of these layers is given below (red is the gold, black is polySi and yellow is TEOS).

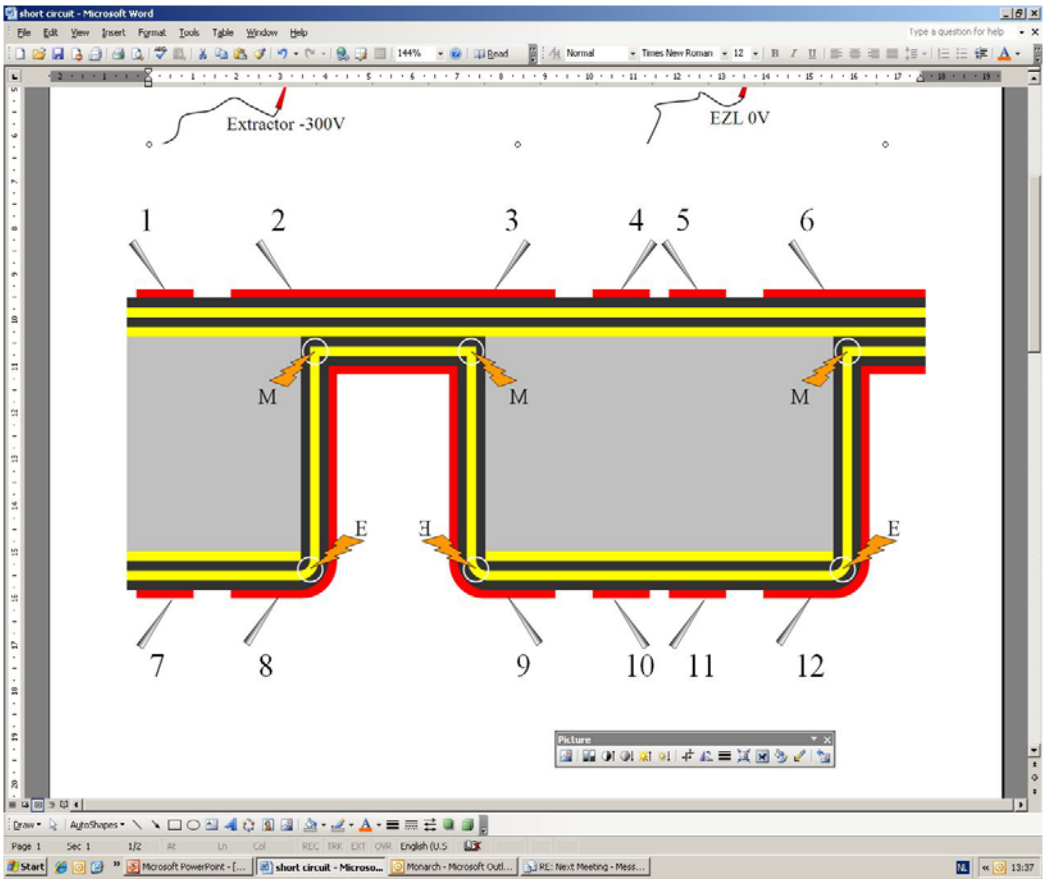


Figure 15 Showing electrode design

When applying a high voltage at position X and measuring the voltage at position Y the following results were obtained (X,Y = 1-12):

X	Y	observation	Conclusion
1	4	current below 1mA up to 1100 Volt	OK
2	4	current below 1mA up to 1100 Volt	OK
7	10	current below 1mA up to 1100 Volt	OK
8	12	non-destructive breakdown above 100 Volt	Faulty

I.e. there appears to be a breakdown at the corners (indicated by the sparks M and E) which drastically reduces the breakdown field strength.

It was suggested at the second Gothenburg meeting (18M), that by connecting the chip in a certain way, the same wafer design could be adapted to provide four physical electrodes, but functionally three. (In other words avoid the short-circuit problem on the chips.) Simulations at Salford and Chalmers subsequently showed that this provided focusing, with higher bias and shorter focal length. *I.e.* the short-circuit problem could be avoided, and the chip would still function as a good lens, but with three electrodes, rather than four.

Modeling work at Salford

The initial designs had been based around computer simulations using the SIMION program. SIMION is an ion optic simulation code that simulated charged particles in two-dimensions. In order to fully evaluate the design in three-dimensions, Lorentz software was utilised, providing three-dimensional charged particle optic simulation. Using Lorentz, the design and beam profile was simulated in three-dimensions and it was confirmed that focusing of the beam spot down to nanometer sizes could be achieved.

Task 1.2 Chip body manufacture process

Studbump contact

The membrane chip and support chip are flip-chip bonded with thermal compression (at 300°C, through studbumps) to get good mechanical and electrical contact. Firstly, two support chips were bonded, good mechanical and electrical connection were shown with this method. This chip stack was then sent to Nanofactory to ensure that it fitted the testing set up, which was successful. When bonding with the membrane chips which have the lithography foil remaining at the surface, the foil was found to melt, and stick to the bonding tool. This shows the foil at the non-bonded sided of the membrane chips has to be stripped.

Llithography with UV-sensitive foil

Lithography with the “normal” liquid resist did not give good coverage at the cavity hole area. MESA+ developed a lithography process with the DuPont UV-sensitive dry film to improve this situation. Due to the deep and wide cavity, the foil were bent and cracked during the lamination and development. It was found that reducing the temperature during laminating prevented the foil bending into the cavity, but made the foil delaminate. The problems were finally solved by first laminating the foil with low temperature and then high temperature and multiple lamination processes.

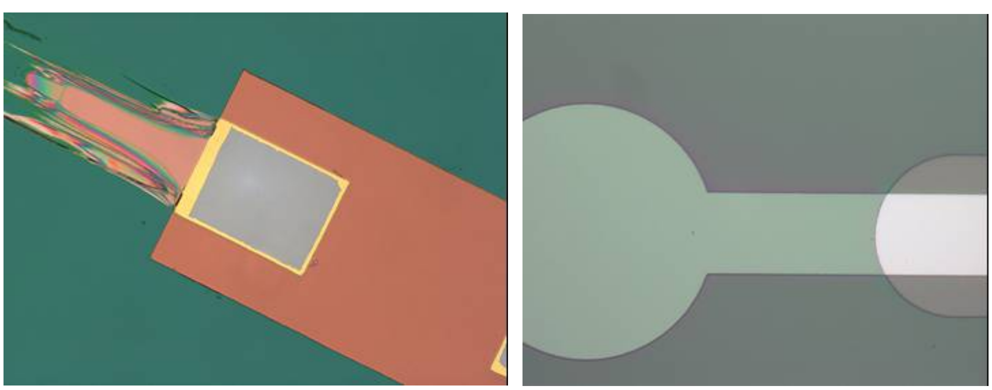


Figure 16 Showing improvement of the adhesion of the foil (LHS original process; RHS MESA+ process)

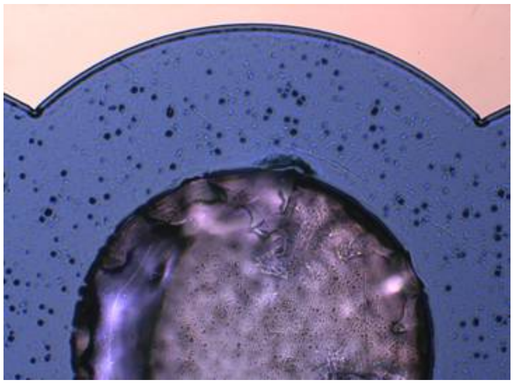
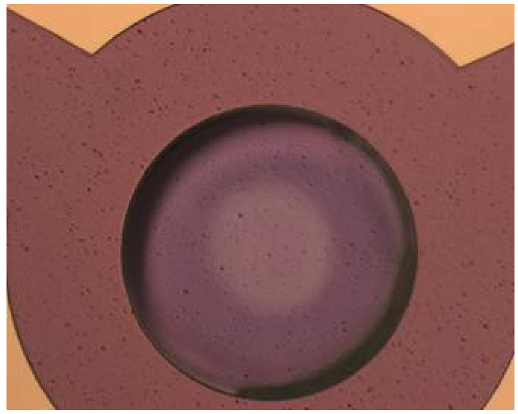
 

Figure 17 Photos of the central chip area showing improvement of the flatness and no cracking

Chip manufacture
One membrane wafer and one support "dummy" wafer were processed successfully. Ten pairs of membrane chips and supports chips were bonded and delivered. See the process flow in the Appendix to D30.

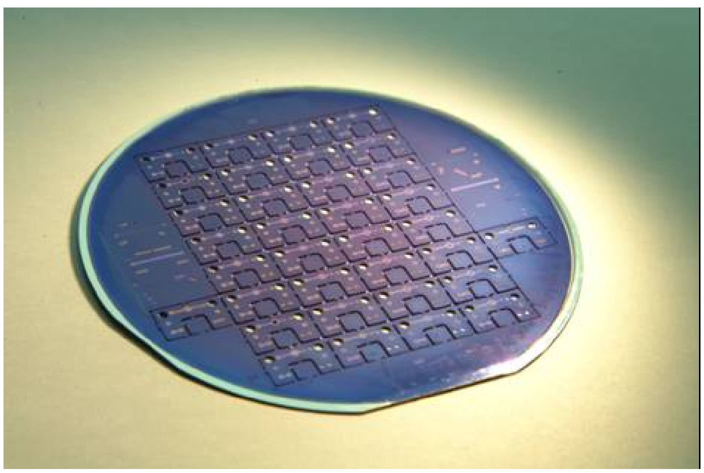


Figure 18 Photo of wafer before chips were broken out

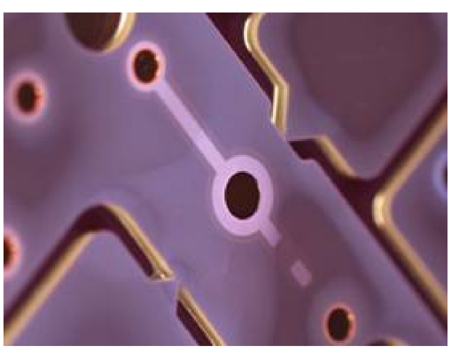
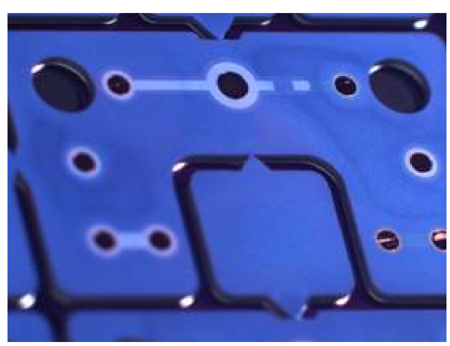
 

Figure 19 Photos showing close up of chip bodies on wafer structure

Figure 20 Photo showing the detector-facing side of the chips with contact points A, B & C

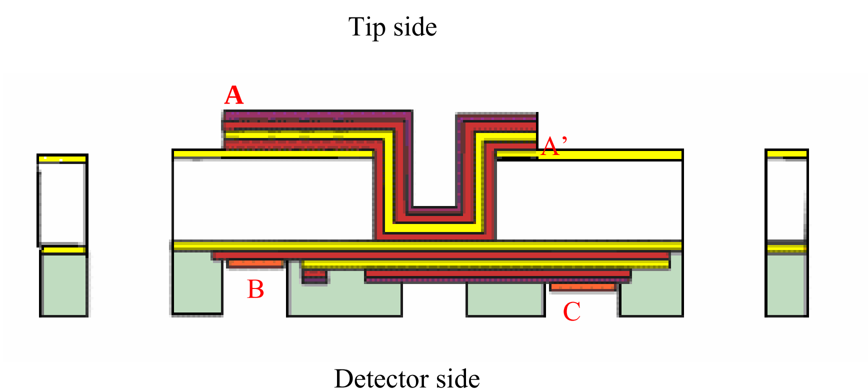


Figure 21 Schematic cross section view of the membrane chip with contact points A, A', B & C

Material of each electrode layer
A: 50nm Pt + 200nm poly-Si
A': 200nm poly-Si
B: 200nm poly-Si
C: 200nm poly-Si + 50nm Pt
Separating insulator: 1000nm TEOS

"Doping" of the Poly-Si electrodes
"B" is doped and A' is not doped.

This process is considered to be robust and repeatable.

Parallel chip work at University of Salford/ NFAB

The D7 design was in the process of being fabricated at the beginning of this reporting period. As a contingency, it was decided to also follow other possible routes and designs for the chip body in order to maximize the probability of success of the project. In order to do this, several third party contractors had been consulted and invited to submit quotations for the fabrication of a second Monarch chip body. These contractors included the Scottish Microelectronics Centre (Edinburgh), Kelvin Nanotechnology (Glasgow) and Cambridge Nanoscience (Cambridge). Of the contractors consulted, two were asked to fabricate some chip bodies – the Scottish Microelectronics Centre (SMC) and Cambridge Nanoscience – of which only one delivered chip bodies, SMC. Upon receipt of the chip bodies from SMC it was discovered that the electrical breakdown properties of the multi-layers rendered the chips unfit for purpose. Full details of the chip designs, materials and problems encountered are outlined in deliverable D10.

Upon receipt of the chip bodies from MESA+, they were successfully tested for electrical breakdown and apertures were then milled into the membrane region of the chip. The chip was again tested for electrical breakdown/continuity (it was anticipated that the Ga from the ion beam could be implanted into the surface regions of the apertures and allow electrical conduction). This test was again successful.

<u>Deviations from the project work programme, and corrective actions taken/suggested</u>

Apart from a slight delay, it appeared that this WP had been fully successful. As has been described, unfortunately there was a problem in the processing of the chip bodies which meant that the electrode structure was not functional. However, this was not discovered until the final two weeks of the project.

<u>List of deliverables</u>

Deliverable No.	Deliverable Title	Due date	Date delivered/ expected
D2	Initial chip body design	Month 3	Month 5 (Delivered)
D7	Final chip body design	Month 12	Month 12 (Delivered)
D10	Optimised process description for chip body manufacture	Month 24	Month 25 (delivered)
D30	EXT Revised chip body design	Month 24	Month 25 (Delivered)
D12	Manufacture of chip bodies for demonstrator	Month 25	Month 28 (Delivered)

<u>List of milestones</u>

Milestone No.	Milestone Title	Due date	Date delivered/ expected
M1	First batch of chip bodies manufactured	Month 6	Month 6 (Delivered)

WORK PACKAGE 2 – NANO-TIP AND APERTURE FABRICATION

Work package objectives

- Definition of process for milling of nano-tips on chip bodies
- Definition of process for forming apertures through accelerating section & objective lens
- Delivery of operational SEM-on-a-chip devices to WP4

Period 1 Progress towards objectives

Task 2.1 FIB milling of nano-tip

Early in the project with the original concept of the uniform tungsten investigations were conducted to see if it was possible to produce a field emitting element through the milling of the tungsten layer. Figure 22 shows a field emission graph obtained from a milled tip.

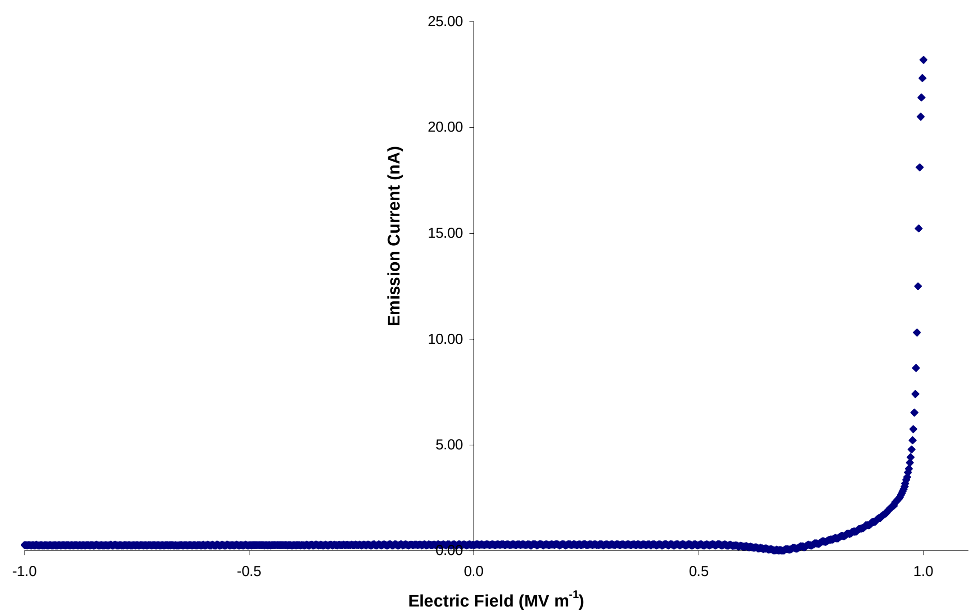


Figure 22 Graph showing the current pass versus electric field for a milled tip.

During the course of the project as the chip design changed, the requirements of the tip changed. As a result there was a focus towards STM style tips with the overall aim to produce a tip that is similar to the “super tips” in the literature which give single site emission. To this end a number of chemical etch tips were produced. The base metal for the STM style needle was tungsten with KOH etchant. A number of variables were investigated including wire thickness and weighting of the wire. It was been decided that a 0.1mm wire of without a weight should be used. This produced a good yield of tips that are comparable with those used as a starting point for “super tip”(Figure 23) and a small number of tips with very small radius of curvature (Figure 24).

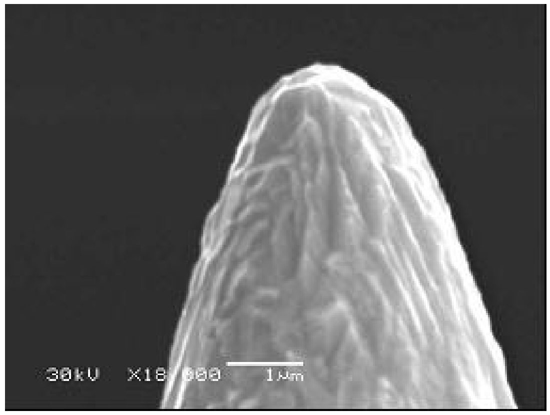


Figure 23 Image of a chemical etched tungsten tip typical of the high yeild type.

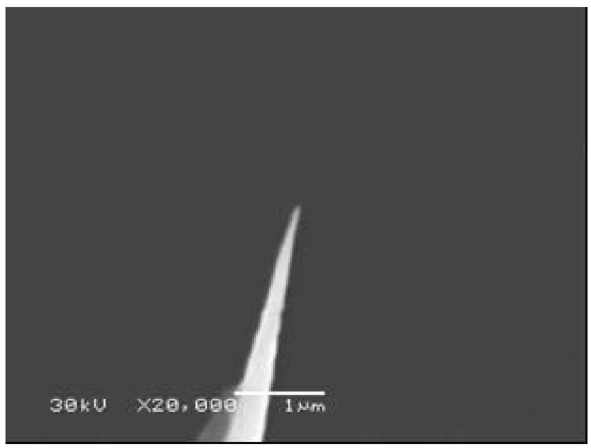


Figure 24 An image of the very small radius of curvature tips that are produced with a very small yield.

Task 2.2 Aperture fabrication

The production of the apertures is an important to the success of the project. To this end effort was put in to investigating the milling of apertures. Holes were milled into the SMC tungsten multilayer and into a membrane consisting of two layers (TEOS and gold) as provided from MESA+. Milling work was performed on the SMC multi-layers resulting in apertures of approximately the size required for successful completion of the project. It was noted that there was some slight distortion from cylindrical symmetry that is preferred. As a result of this and discussion in the technical meeting held in November 2007, it was decided to undergo a series of experiments whereby a through focus series of the ion beam is used and a series in which the specimen stage is tilted slightly in order to try and determine the nature of this non-cylindrical symmetry. Work on the MESA+ membranes has not been successful due to a blow-out of the membrane during insertion into the vacuum chamber of the microscope. This problem may be simply circumvented and this work will continue in the future.

In addition to the milling of holes, the edges of the multi-layers have been observed and the differences between the tungsten and gold chips. It was noted during this work that there maybe some possibility of short circuiting of the layers on both sets of chips due to slightly irregular edges. It is thought that the gold chips would prove the most difficult to eliminate the shorts due to the smearing of the gold layers whereas the tungsten multi-layer may be polished using TEM specimen preparation techniques to reduce the possibility of shorting.

Task 2.3 UHV testing of beam quality

Work has been conducted in the design and building of a UHV system for far field measurements for both tip and tip and body assembles. The UHV system has been designed to minimise the oil contamination through the use of oil free pumps. A scroll pump for backing an oil free turbo pump and an ion pump. The system has also be design to minimise vibrations firstly with the chamber being mounted on an optical bench. It can also operate in a "low vibration mode" where the chamber is taken down to pressure using the scroll and turbo pump and then the main chamber is isolated and the pressure maintained by the ion pump.

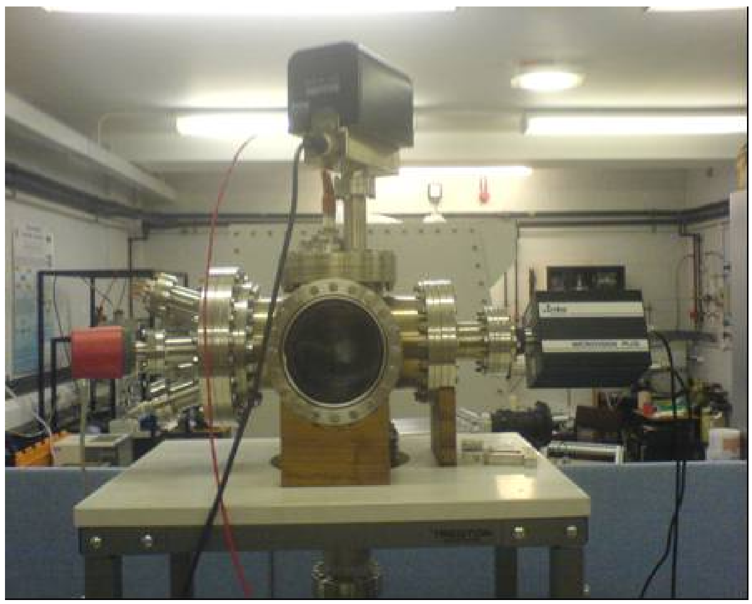


Figure 25 Picture of the UHV system at University of Salford

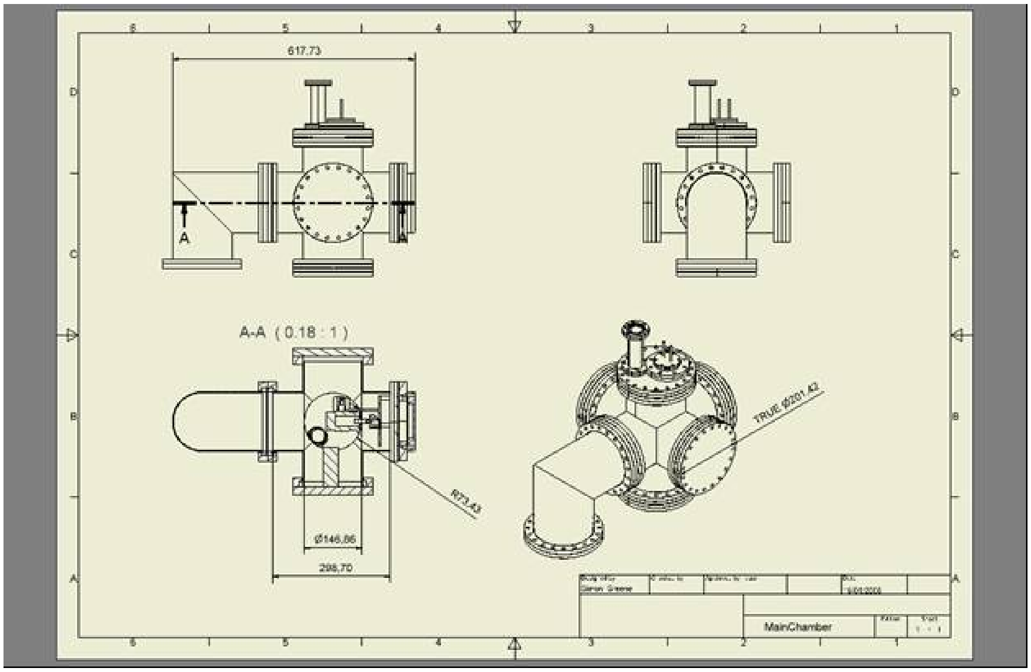


Figure 26 CAD drawing of the the main body of the UHV system at the University of Salford

In addition to the the vacuum chamber a far field measurement system has been designed. This system is based on a MCP and phosorur detector system and a nano-positioner placement system, and should allow for real time two-dimsional beam profile imaging of the SEM beam in the far field.

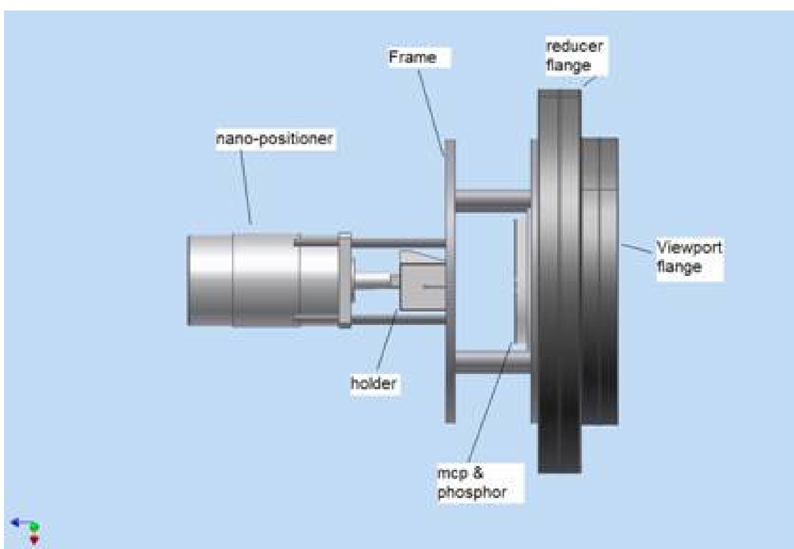


Figure 27 CAD model of the far field measurement sysetm for the the Nano-SEM

Period 2 Progress towards objectives

Starting point of work at beginning of reporting period

-Tips: By the beginning of 2008, it had been decided that a 2D approach to tip fabrication would not be continued (due to changes in the design of the chip body) and that a 3D nano-tip would be fabricated. This investigation included, but was not limited to, carbon nano-tubes grown on a cut tungsten tip, a cut gold tip (for the purposes of rough testing) and the fabrication of a super-tip (gold pyramids grown on pre-etched, orientated tungsten tips).

-Aperture fabrication was at a relatively advanced stage and the process definition for the fabrication of apertures on the chip body had been defined. Due to delays in the delivery of the chip bodies, no apertures had yet been fabricated on the chips bodies for the demonstrator.

Task 2.1 FIB milling of nano-tip

As described in the revised Technical Annex (Oct-08), several routes to nanotips were explored. These are described in detail in D15. Some key findings are summarised below. The tips that were fabricated were characterised in the vacuum system be recording current-voltage (I-V) curves, the plotting of Fowler-Nordheim graphs and by the imaging of the beam spot on a phosphor screen (the signal being amplified through a multi-channel plate).

Carbon nanotubes

First, Pt/Ir (80/20) tips were obtained by cutting a 0.25 mm thick wire. Second, oxygen plasma was applied to some of those tips for comparison. A low outgassing conductive epoxy (H27D from EPOTEK) was then used to place double walled carbon nanotube bundles (series 2100 from NANOCYL) onto the tip. A curing stage was then carried out, where the tips were left for 1 hour inside an oven at 150ºC, followed by an increased temperature phase at 250ºC for 10 min, then the temperature was decreased back to 150ºC for 20 min, and finally the tips were left to cool down for 10 min in the oven. The electrical resistance of the conductive epoxy was measured after the curing stage, and was found to be less than 0,3 Ω/cm.

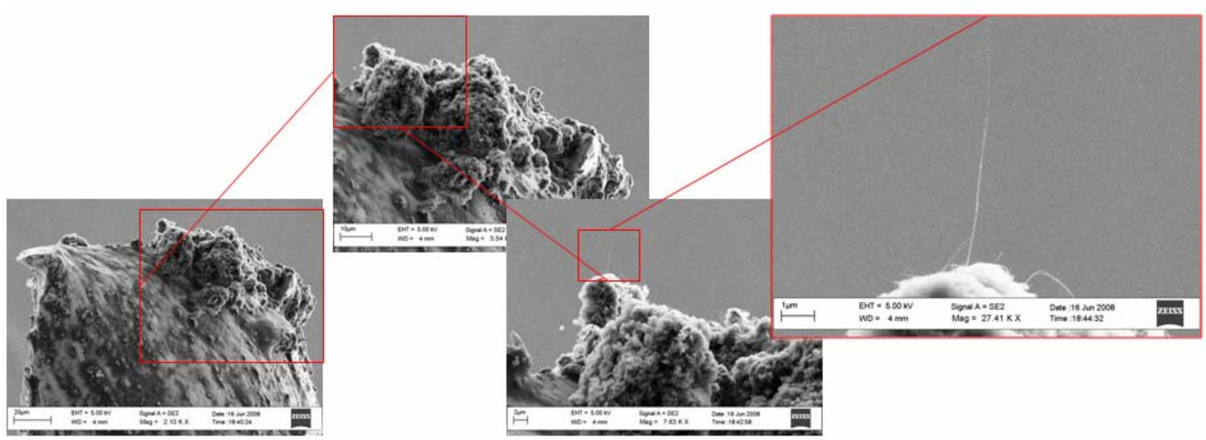


Figure 28 Carbon nanotube bundles had random sizes and directions, thus not so many tips were as successful as this particular tip which had a single tube pointing in a favorable direction

SEM pictures revealed that most tips did not have a single carbon nanotube at the required tip position, but rather had a bundle of tips in random directions. Subsequently, ten tips were sent to Salford University for further investigations. These CNTs were characterised in the vacuum chamber for their field emission characteristics.

Etched tungsten: in-situ sharpening ("etch & stretch")

An etched tungsten tip was moved into contact with a 200nm platinum layer, and then a voltage was applied between the tip and the layer causing a current to flow. The resulting heating effect caused the removal of the tungsten oxide from the tip's end as seen below.

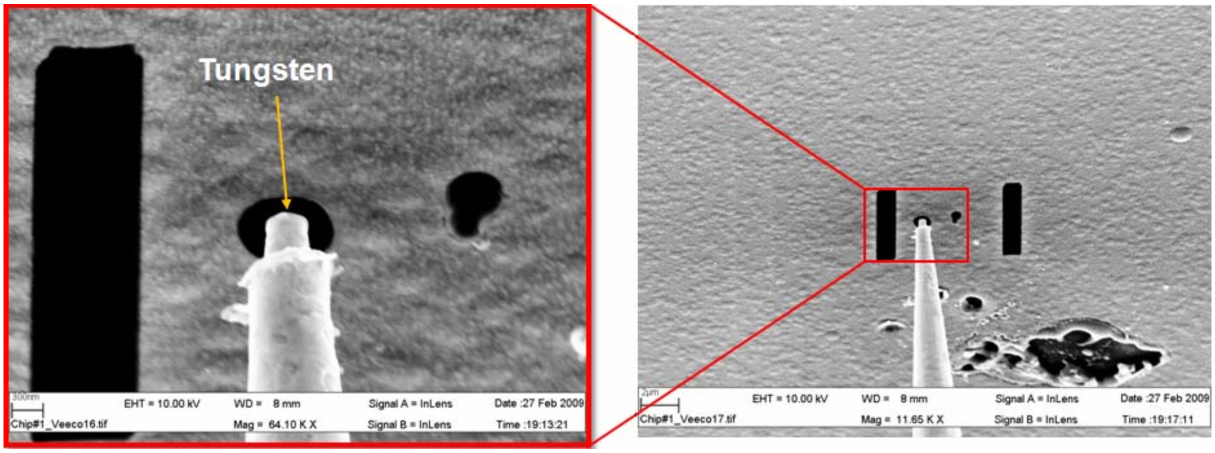


Figure 29: Removing the tungsten oxide layer was possible by localized heating at the tip

Further heating was applied until the bare tungsten melted, and by retracting the tip away from the surface, an atomically sharp tip was created. This interesting result will be explored more thoroughly after the project completion.

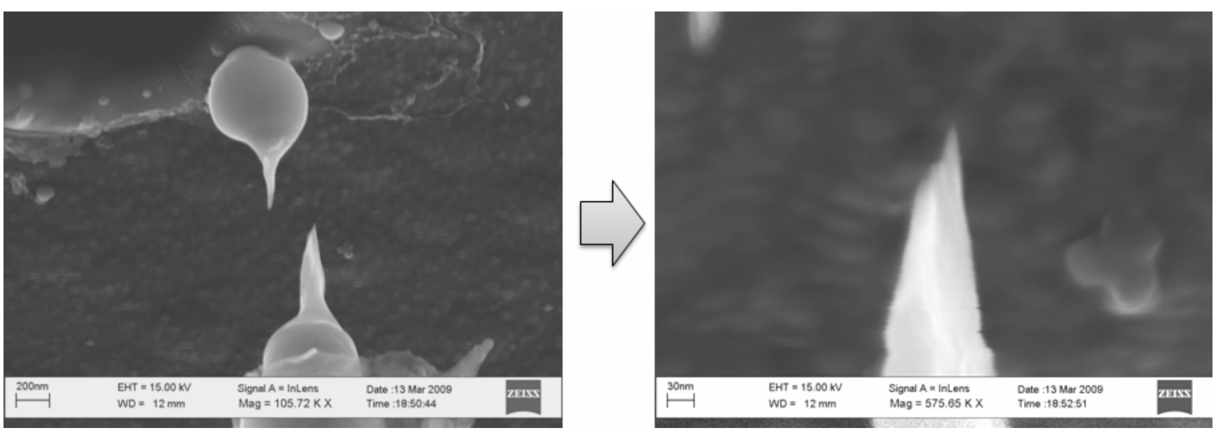


Figure 30 With further software control, our tip sharpening technique can be an alternative to producing oxide-free atomic tungsten tips

Other tip materials

A range of other tips were investigated including: nickel, gold, molybdenum, tungsten and platinum/ iridium.

Supertips
NFAB employed an expert in the manufacture of supertips to assist with this work, and he proved an extremely capable scientist. Preparations for the fabrication of super-tips included the practice of pre-etching tungsten tips using conventional electro-chemical techniques using poly-crystalline tungsten wire. This was required due to the difficulties in obtaining the highly orientated (111) tungsten wire needed for the fabrication. In addition, a preparation chamber for the super-tips was designed and added to the existing vacuum chamber so that the pre-etched (111) tungsten tips could have gold deposited onto the surface and then be conditioned in situ to form the super-tip. This included the initial cleaning (removal of the native oxide) of the tip through electron bombardment followed by the thermal deposition of the gold onto the tip. The tip would then be moved to a different area of the chamber for conditioning whereby the tip would be heated slightly, again using electron bombardment, whilst an electric field was applied to the tip. This allows the gold atoms to migrate on the surface of the tungsten to preferentially form pyramids at the apex of the tip with one gold atom at the apex of the pyramid. However, due to time constraints most effort focused on other tip technologies. Supertips is a topic which will be pursued outside of the Monarch framework.

Task 2.2 Aperture fabrication
The process through which apertures would be formed on the chip bodies had been defined prior to this reporting period and immediately following the delivery of the chip bodies in Month 21, apertures were successfully milled into the membrane of the chip.

To reduce the drifting problems, only low-current milling ion beams (below 10 pA, at 30 kV) are chosen (as shown in Figure 5). Moreover, a special holder was developed to ensure grounding all the four element-layers while milling the final chips.

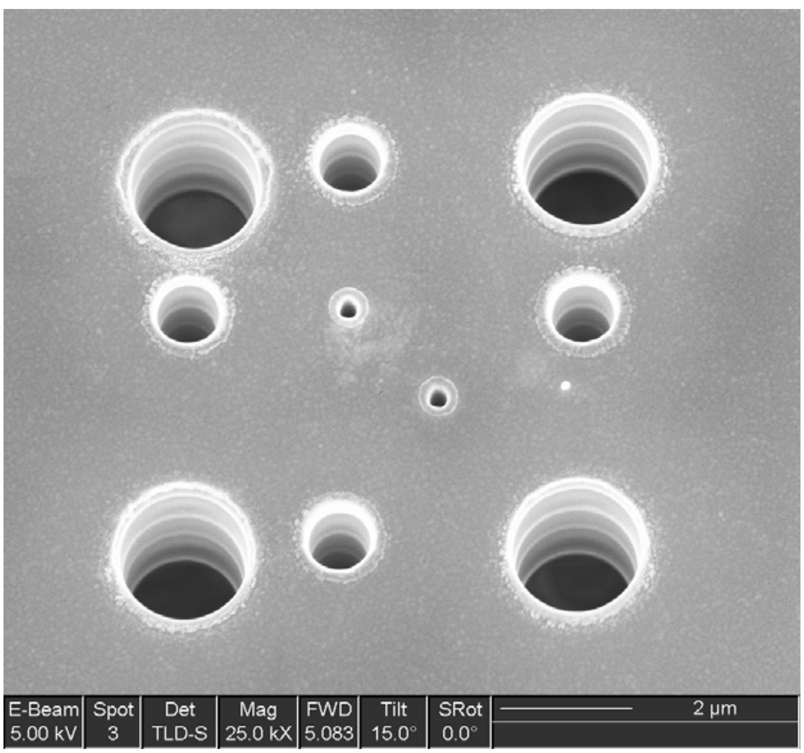


Figure 31 Dummy chip # 2 showing little drift after milling apertures with different sizes at 30 kV and 10 pA; also visible are the four lens layers with a brighter contrast than the insulator spacings.

Task 2.3 UHV testing of beam quality

At Salford, a single-sided holder (tip, nano-manipulator and chip mount) was tested, using the chip from MESA+/C2V. The tests were performed in a UHV chamber, using a fluorescent screen for detection of a transmitted electron beam. It was successfully demonstrated that the nanopositioning system was capable of positioning the tip at the right position relative to the entrance aperture of the chip, the tip could be biased to extract an electron beam and the beam was transmitted through the chip onto the screen.

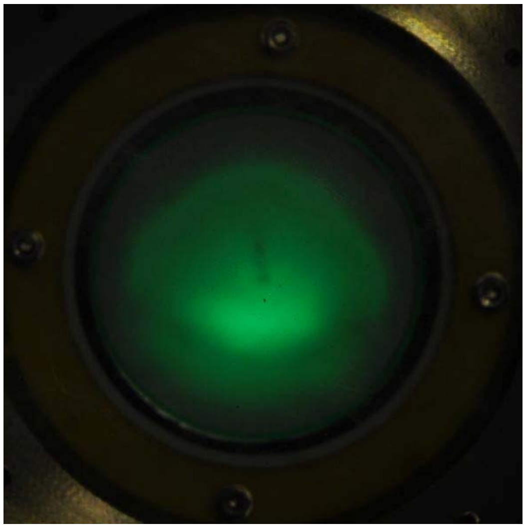


Figure 32 Transmitted beam imaged on the flourescent screen (Salford UHV tests).

Further tests were carried out using a beam from an SEM to show that the detector and scanning system functioned correctly (see WP4.2).

Obviously due to the lack of electrode structure in the chip, no focusing into a beam was possible.

<u>Deviations from the project work programme, and corrective actions taken/suggested</u>

Tips- The supertips potentially provide the best solution, but there was not sufficient time to explore this method. However, several other solutions were demonstrated.

Apertures- Problems in optimising the aperture milling process were encountered, including drift of the beam during milling (resulting in non-circular holes), gallium deposits in the apertures and FIB aberrations. However, these were all overcome through careful technical optimisation and a successful process was defined.

Beam quality- Obviously this was severely affected by the lack of focusing electrodes on the chip. Because this problem was only discovered in the last two weeks of the project no mitigating action was possible. However, it was shown that all the elements of the system functioned as expected: tips, apertures, nano-positioner and detector (see WP4.2).

List of deliverables

No.	Deliverable Title	Due date	Date delivered/ expected
D14	FIB widening process definition	17	Completed M19
D15	Manufacture of nano-tips for demonstrator	25	Completed M25
D16	Apertures formed on chips for demonstrator	26	Completed M25
D17	Report on beam profile of nano-electron source	28	Completed M30

List of milestones

No.	Milestone Title	Due date	Date delivered/ expected
M2	First nano-tip formed	Month 9	Month 9 (Delivered)
M3	First pilot holes drilled	Month 12	Month 12 (Delivered)
M4	Optimised process description for nano-milling of nano-tip	Month 16	Month 20 (Delivered)

WORK PACKAGE 3 – DETECTOR IMPLEMENTATION

Work package objectives

- Modification of annular detector
- Integration of annular detector with modified sample scanning process
- Delivery of operating detectors integrated with SEM-on-a-chip devices to WP4

Period 1: Progress towards objectives

Task 3.1 Detector development
Chalmers demonstrated controlled movement of a field-emitter, *i.e*. M7 complete.

Field emission on produced chips from WP1 tested and this provided vital information for the future design.

The detection system designed. Chalmers has opted for a commercial single channel electron multiplier.

Period 2: Progress towards objectives

Starting point of work at beginning of reporting period

- Detection concept selected
- Detection electronics selected

Task 3.1 Detector development
The following keys steps were achieved in the successful implementation of this WP:

- Detector acquired
- Holder system developed
- Detection electronics acquired
- Detection software developed
- Detector tests specified (that are independent on Chip progress)
- Detector tested separately and together with image acquisition software.

The detector was mounted as close as possible to the sample in order to have a large solid angle of detection. The performance was tested inside an SEM in order to get a performance test of the channeltron that is independent of the chip. A picture of the setup inside the SEM is shown below. By using the SEM beam on the sample as a substitute for an electron beam from the chip, the channeltron and associated hardware could be tested and evaluated independently of the chip.

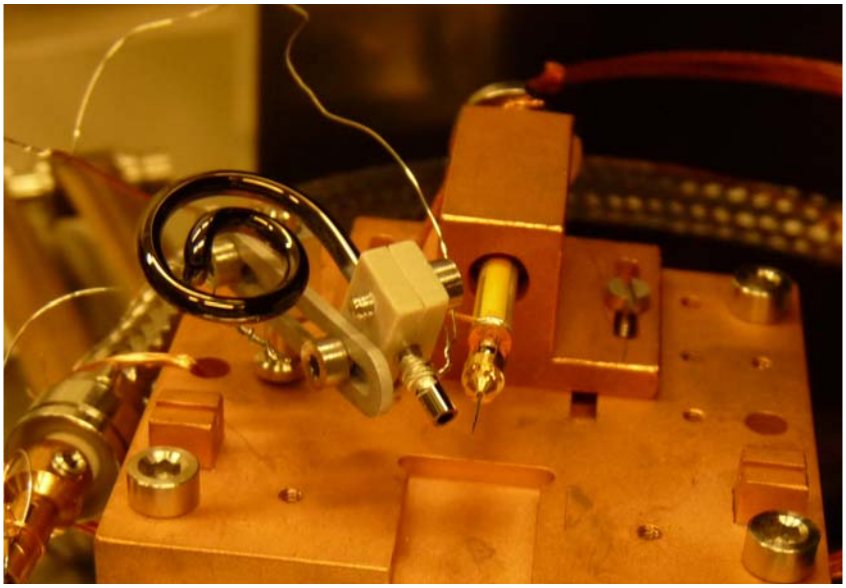


Figure 33 Photo showing sample holder with channeltron detector

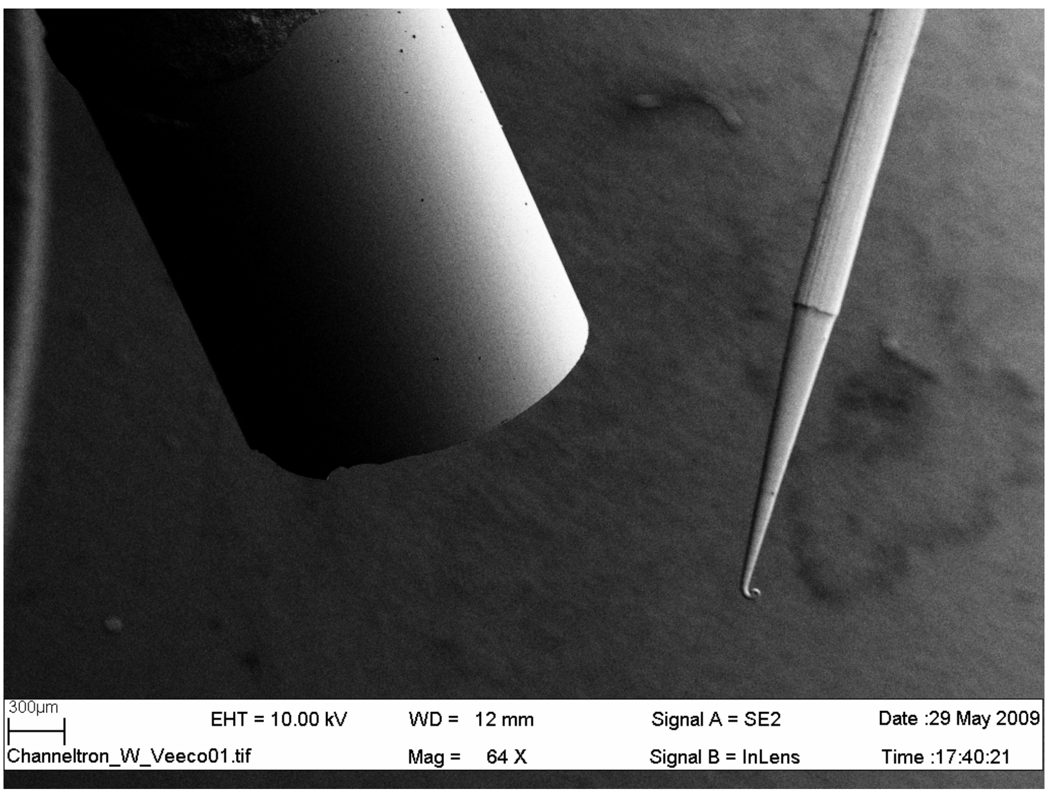


Figure 34 Sample tip in front of the channeltron detector

Figure 35 Holder for sample and channeltron mounted inside the SEM

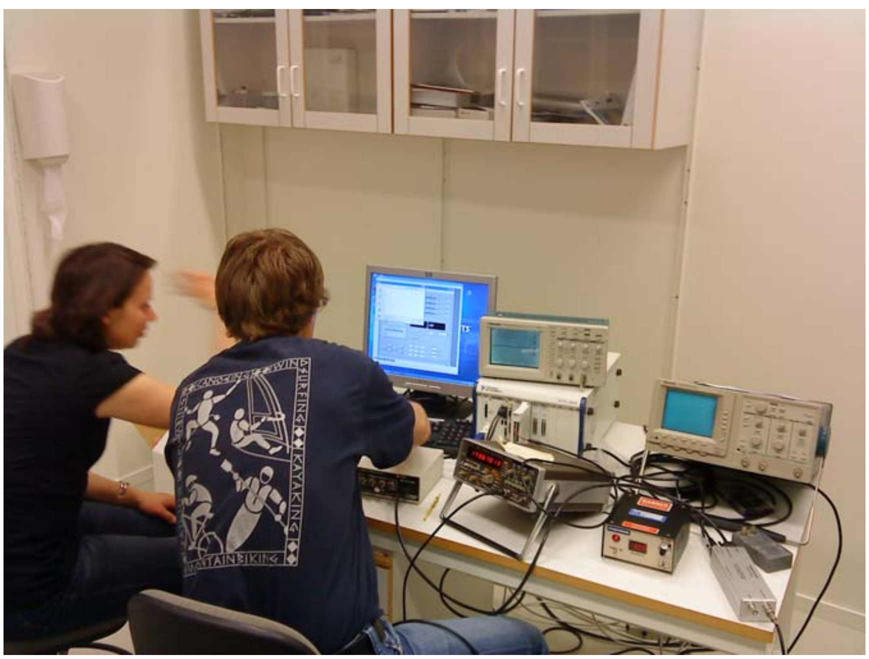


Figure 36 Ensemble of measurement equipment containing of channeltron on holder combined with sample holder, detection electronics and measurement electronics.

Scanning mode tests

The SEM beam was used for testing the performance in an image acquisition mode. By keeping the SEM beam stationary the sample was scanned in a plane perpendicular to the beam in order to emulate a fully working chip and image acquisition system. An SEM image of the sample area is shown below together with an image acquired using the setup (*i.e.*

scanning the sample while detecting backscattered electrons). Good correlation was observed between the images and this demonstrates that the system would work when provided with a stable, and focused, beam from a chip.

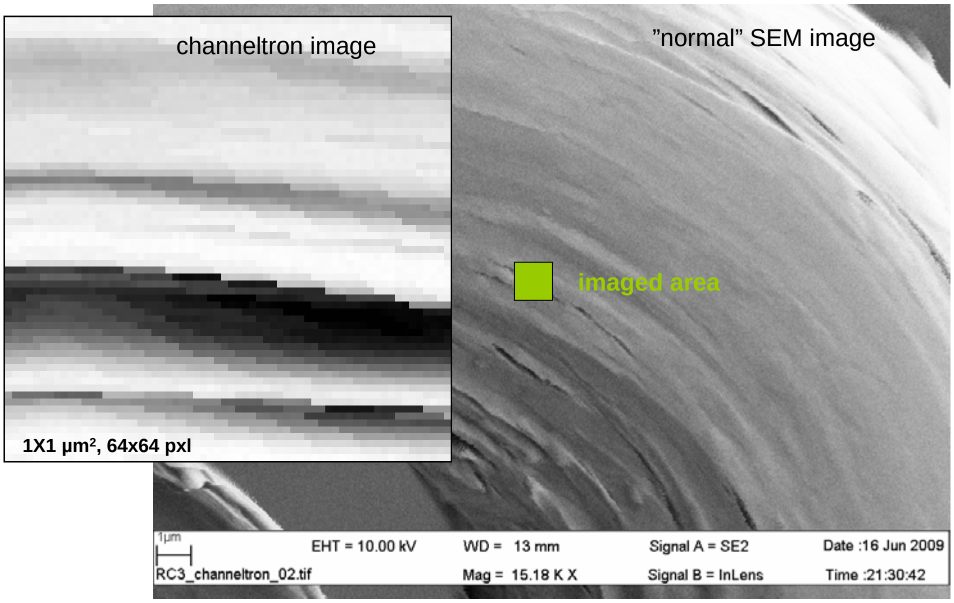


Figure 37 SEM image of the sample together with an image acquired with the Monarch setup when using the SEM beam to emulate an electron beam from the chip.

Deviations from the project work programme, and corrective actions taken/suggested

As has been explained, the final chips could not deliver a focused electron beam so the detector had to be tested independently of the chip. A stationary electron beam of the SEM was used to emulate an electron beam from the chip and it was demonstrated that the detector system is fully operational with a very good signal to noise ratio.

List of deliverables

No.	Deliverable Title	Due date	Date delivered/ expected
D13	Operational integrated detector	Month 26	Month 29 (Delivered)
D19	Optimised detector & SEM-on-a-chip operational	Month 28	Month 29 (Delivered)

List of milestones

No.	Milestone Title	Due date	Date delivered/ expected
M5	Design of integrated detector	Month 8	Month 12 (Delivered)
M6	Detection of scattered electrons from SEM-on-a-chip	Month 28	Month 29 (Delivered)
M7	Nano-manipulator operation demonstrated	Month 12	Month 12 (Delivered)
M9	Demonstration of modified scanning software	Month 25	Month 25 (Delivered)

WORK PACKAGE 4 – SYSTEM INTEGRATION

Work package objectives

- Delivery of modified UHV system compatible with SEM-on-a-chip device
- Integration of SEM-on-a-chip with nano-positioning probe
- Testing of demonstrator SEM-on-a-chip system.

Period 1: Progress towards objectives

Task 4.1 Integration with UHV system

A prototype system, optimised for use inside a standard SEM was developed and tested by Month 6. Based on this system, a UHV compatible platform (termed UHV1) was developed. In parallel with UHV1, a system with double piezo scanners, called UHV2, was under development.

The UHV2 system is based on UHV1, but besides consisting of scanners for both the tip and the sample, it also includes new electronics and software to enable control of the two scanners. These new electronics also provide higher stability of the nano-positioning devices (better than 0.3 Å).

The systems were developed in close collaboration with Chalmers University of Technology, where the actual UHV chamber was placed. All systems are designed to fit inside a standard SEM, to be used for evaluation purposes. The UHV1 and UHV2 systems are being designed to fit inside the UHV system at Salford University and will be able to accommodate the chip bodies developed by University of Twente and Salford University.

Period 2: Progress towards objectives

Starting point of work at beginning of reporting period

- Prototype nano-manipulator for use in SEM delivered (Nanofactory)
- Prototype control electronics for running the scanner prototype delivered (Nanofactory)
- UHV nano-manipulator in design stage (Nanofactory)
- Concept for control electronics and software (PXI/LabView) selected (Nanofactory)
- Detector concept selected (Chalmers)
- Chips under development (MESA+)
- UHV system designed and built at Salford
- UHV system in progress at Chalmers.

Task 4.1 Integration with UHV system

WP4 took outputs from WP1-3 in order to integrate them into a dedicated ultra-high vacuum (UHV) prototype system to demonstrate the full potential of the SEM-on-a-chip system. This practical work package required engineering and vacuum system skills, in order to build a UHV system to accommodate the SEM-on-a-chip and its detector system. The planned final part of the project was an extensive test of the assembled prototype of the system to establish and document its capabilities. The demonstrator SEM-on-a-chip was the main deliverable from WP4.

Delivery of the chip body/tip side of the SEM-on-a-chip device was taken from Nanofactory in the first half of 2008. This allowed for the familiarisation of the equipment prior to the delivery of the chip bodies using a cut gold tip and a platinum coated silicon substrate.

Following delivery of the chip bodies and subsequent formation of the apertures, this system was used to characterise the electron beam through the measurement of current-voltage (I-V) curves, plotting of Fowler-Nordheim graphs, and through the measurement of the beam spot as imaged on a phosphor screen following emission through the apertures.

January 2009 saw the delivery of the sample side of the SEM-on-a-chip device from Nanofactory, thus completing the demonstrator device.

Salford UHV system

The system used a dry backing pump (scroll) and an oil-free turbo pump (TMP) that could be gated off from the main chamber along with an ion getter pump that would generate and maintain ultra high vacuum levels with the TMP turned off and isolated by means of the gate valve. This was all mounted on a vibration damped, optical bench. This ensured that testing of the system could be performed vibration free.

Chalmers UHV system

A dedicated UHV system was developed that provides rapid pump-down and bake out times combined with a high mechanical stability (*e.g.* by use of a high pumping speed turbo during bake-out and an ion-pump during operation of the source). This system could accommodate the SEM-on-a-chip on its nano-manipulator, the detector and the sample-positioning interferometer for testing.

Holder

Based on Nanofactory's proprietary technology, a UHV device (the holder) for demonstrating the SEM-on-a-chip was designed and manufactured. The holder comprises two nano-manipulators, a device for mounting and contacting the chip (chip mount) and an integrated detector, based on a channeltron electron multiplier. A design sketch of the holder is shown below.

The first of the two nano-manipulators (tip manipulator) is used for positioning the electron emitter (the tip) at the correct position relative the extraction aperture (the first aperture of the chip). The chip mount has four spring-loaded contacts, so that the chip can easily be exchanged without soldering.

The second nano-manipulator (sample manipulator) is used to position and scan the sample relative to the electron beam. The channeltron detector is used to collect secondary electrons from the sample, amplify the signal and feed it to the counting electronics.

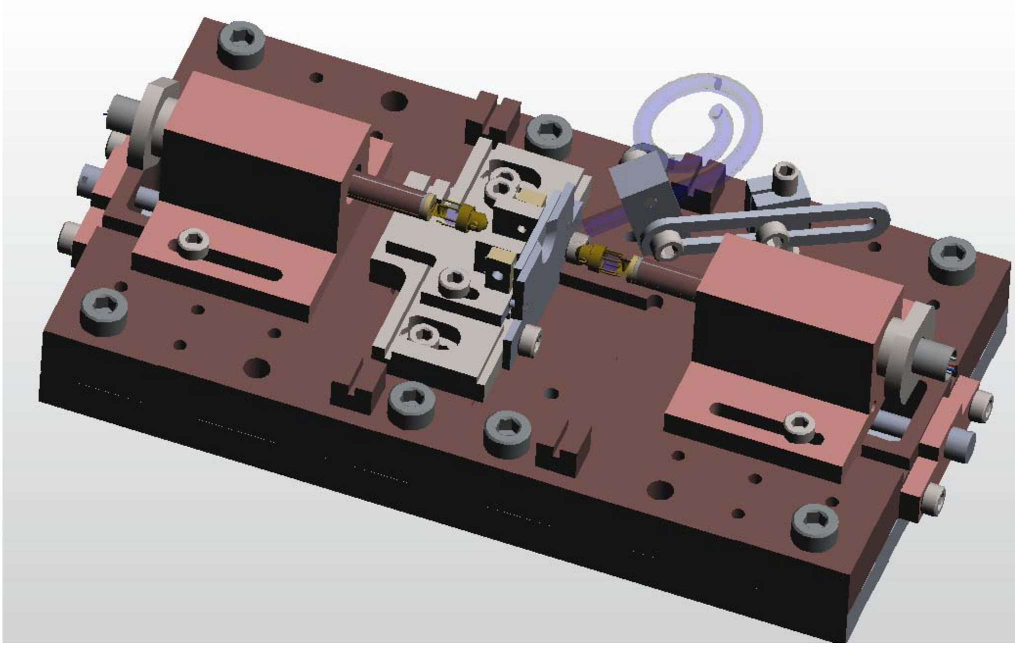


Figure 38 Design sketch of the nano-positioning system.

Control system
The holder is controlled by a control system. The system was developed based on National Instruments PXI and LabView standard modules, and contains subsystems for controlling the two nano-manipulators, applying and measuring potentials and currents to the chip and tip, and collecting the signal from the detector. The system is controlled and the data is collected by a LabView based program.

Task 4.2 Final testing

Salford testing
Emission tests were carried out at Salford as described in WP2.3. A single-sided holder (tip nano-manipulator and chip mount) was tested, using the chip from MESA+/C2V. The tests were performed in a UHV chamber, using a fluorescent screen for detection of a transmitted electron beam. It was successfully demonstrated that the nano-positioning system was capable of positioning the tip at the right position relative to the entrance aperture of the chip, the tip could be biased to extract an electron beam and the beam was transmitted through the chip onto the screen.

Chalmers testing
A similar test was performed at Chalmers, but in this case, the tests were performed inside the vacuum chamber of an existing SEM. The SEM was used for additional monitoring of the tip's approach to the chip. Here, the beam transmitted through the chip was detected using two wires to collect the current from the beam. Deflector plates were used to deflect the beam and investigate the beam's spatial distribution.

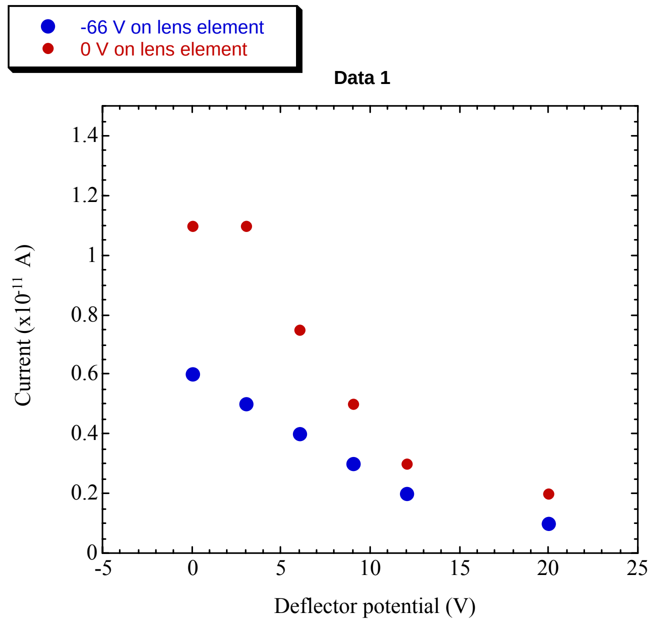


Figure 39 Transmitted beam studied by collecting the beam current onto a wire (Chalmers tests inside SEM).

Deviations from the project work programme, and corrective actions taken/suggested

All tasks were accomplished as expected.

List of deliverables

No.	Deliverable Title	Due date	Date delivered/ expected
D11	Fabrication of UHV system	Month 15	Month 16 (Delivered)
D22	Operational SEM-on-a-chip demonstrator system	Month 28	Month 29 (Delivered)
D23	Report on performance of SEM-on-a-chip demonstrator system	Month 30	Month 30 (Delivered)

List of milestones

No.	Milestone Title	Due date	Date delivered/ expected
M10	Demonstration of nano-manipulation	Month 25	Month 27 (Delivered)

WORK PACKAGE 6 – EXPLOITATION AND DISSEMINATION

Work package objectives

- To develop the MONARCH website to act as an efficient dissemination tool
- To promote the project, its results and its potential to the European research community and the wider public
- To host two technology transfer workshops for interested parties, potential customers and licensees
- To diffuse the project's results to industry, general public and European standards bodies
- To generate commercial links necessary to bring the new SEM-on-a-chip to market.

Period 1: Progress towards objectives

Task 6.1 Exploitation planning
Due to the sensitive nature of the development work, it was decided to restrict the public material in Year 1 of the project.

Task 6.2 Project promotion
Dissemination is considered an important part of the project because it is one clear way in which the results of the research can lead to wealth creation. However it is obviously in the interests of the project partners that no results can be disseminated before they have been adequately patented.

It is convenient to divide the project into two parts, the design and the engineering. The former was by now well established and is extensively patented and so a two stranded approach to its was adopted: dissemination-academic papers at meetings (and in Journals) concerned with electron and near field microscopy which are planned for in 2008 and representation at commercial shows which are often allied with academic meetings.

Period 2: Progress towards objectives

Starting point of work at beginning of reporting period

- Website online
- Preliminary publicity activity *e.g.* EMAG-07
- Poster and brochure D5 available

Task 6.1 Exploitation planning & Task 6.2 Project promotion
Dissemination activity was an important part of Monarch in the second period. A great deal of work was carried out which is summarised below:

Media exposure

- Monarch featured on SKY News 21-Apr-08. As part of a 10min feature on nanotechnology Ron Petersen (NFAB) gave an description of nanotechnology and the Monarch objectives and a "Layman's summary" of the project.

- A New Scientist article on NFAB and the Monarch project appeared in the 13-Jun-08 issue. "'Microscope on a chip' to give four times the detail".

- ZDNet online article (16-Jun-08) published "Nanoscale microscope on a chip".

- "Nextbigfuture" online magazine article (19-Jun-08): "Miniature scanning electron microscopes on a chip".

- Nanotechnology Newsletter issued by NIL Technology (20-Jun-08) featured NFAB and Monarch "Nanoscale microscope on a chip".

- Monarch and its potential applications was the subject of a Frost and Sullivan industry "Technical Insights" report article "Nanotechnology Makes Electron Holograms Possible" in an "Inside R&D Alert" 01-Aug-08 (Frost & Sullivan). This article makes specific reference to Monarch and lists the project partners.

- Aug-08 Article on NFAB and the Monarch project appeared in the popular technical magazine "Nano".

Brochures and posters

- A modified version of the EMAG poster was circulated electronically to all partners and put on the MONARCH website in May-08. This poster was presented at trade shows and conferences during the normal business activities of the consortium, particularly NFAB, C2V and Nanofactory. These include Pittcon 2008 (New Orleans, USA; http://www.pittcon.org) and Het Instrument (Utrecht, Netherlands; http://www.hetinstrument.nl/2008/en/).

- A handout brochure (D5) was circulated electronically to all partners and put on the MONARCH website in May-08. This document was available for download from partners' websites, and printed copies were handed out at trade shows and conferences during the normal business activities of the consortium, particularly NFAB, C2V and Nanofactory. These include Pittcon 2008 (New Orleans, USA; http://www.pittcon.org) and Het Instrument (Utrecht, Netherlands; http://www.hetinstrument.nl/2008/en/).

- The handout brochure (D5) was printed (1500 copies) and posted to all partners in Aug-08. These leaflets were handed out at trade shows and conferences during the normal business activities of the consortium, particularly NFAB, C2V and Nanofactory. These include Pittcon 2008 (New Orleans, USA; http://www.pittcon.org) and Het Instrument (Utrecht, Netherlands; http://www.hetinstrument.nl/2008/en/).

- Nanofactory display Monarch poster and distribute hand-outs at European Microscopy Society Meeting EMS-08 (Aachen) (01-Sep-08).

- A video intended for the Salford University website and UTube was recorded by workers at NFAB and Salford (12-Dec-08). (Unfortunately due to technical difficulties it was not possible to put this video online.)

Workshops and conferences

- EMAG 2007 3-7 Sep, Glasgow: NFAB exhibited a poster at Electron Microscopy and Analysis Group Conference 2007 (EMAG 2007) show, and gave a presentation on the technology (>100 attendees). The presentation was very well received with particular interest from US and Japanese electron microscope manufacturers. Note that technical detail was not presented for confidentiality reasons, but there were specific enquiries from these competing companies.

- A workshop was held at University of Salford 18-20 Jun-08 on “The Use of In-Situ TEM/Ion Accelerator Techniques in the Study of Radiation Damage in Solids-A workshop for early-stage researchers”. This was attended by around fifty delegates. The closing Keynote Lecture was given by Andrew Bleloch from NFAB on “Opportunities for Combining Low Aberration Electron and Ion Columns” and discussed the principles, partners and work of the Monarch project.

- NFAB presentation (04-May-09) at SPIE Scanning Microscopy (Monterey, USA) “Construction of a new type of low-energy, scanning electron microscope with atomic resolution” This paper describes the progress of the Monarch project, explores some of the potential applications and acknowledges the FP6 support.

- As part of the EC-funded Tempus project (University of Sohar, Egypt.), Dr. Phil Edmondson presented a lecture entitled “Characterisation of Thin Films using Electron Microscopy – Part 3” (22-May-09). This included a description of the Monarch project and acknowledged the FP6 support.

Academic publications

- Journal of Applied Physics, Volume **105**, Issue 1; paper published "A sub-miniature, low energy, scanning electron microscope with atomic resolution" (13-Jan-09). This paper describes the physics behind the Monarch project and acknowledges the FP6 support. [J. App Phys **105**, 014702 (2009), pp. 014702-014702-3 (2009).]

- Virtual Journal Biological Physics Research, Volume **17**, Issue 2, Instrumentation Development (15-Jan-09) "A sub-miniature, low energy, scanning electron microscope with atomic resolution" The J. App Phys article was selected for Journal Biological Physics Research (15-Jan-09).

Websites

- The Monarch website was maintained throughout the project (and will stay live for the foreseeable future)
  - www.monarchproject.org

- Chalmers University updated its website to include a full page on Monarch with the latest results (29-May-09).
  - http://www.chalmers.se/mc2/EN/laboratories/bionano-systems/research/micro-nanosystems-group/monarch

- Salford University Microscopy Centre updated its website to include a full page on Monarch with the latest results (22-Jun-09)
  - http://www.cse.salford.ac.uk/sumc/monarch.php

Deviations from the project work programme, and corrective actions taken/suggested

It was agreed with the project officer (May-09) that specific workshops were not an appropriate form of dissemination for the project, and that a combination of other activities would provide a more useful dissemination of the project, given its confidentiality considerations and the project progress.

List of deliverables

No.	Deliverable Title	Due date	Date delivered/ expected
D5	First promotional leaflet produced	Month 3	Month 9 (Delivered)
D18	First technology transfer workshop	Month 18	Month 18 (Alternative)
D21	‘Sales’ brochure produced	Month 27	Month 29 (Delivered)
D26	Second promotional leaflet produced	Month 30	Month 30 (Delivered)
D27	Second technology transfer workshop	Month 30	Month 30 (Alternative)
D28	Technology transfer programme report	Month 30	Month 30 (Delivered)
D29	Publications in peer-reviewed journals	Month 24	Month 9 (Delivered)

List of milestones

There are no milestones in Work Package 6.

3 – CONSORTIUM MANAGEMENT

CONSORTIUM MANAGEMENT TASKS

WORK PACKAGE 5 – PROJECT MANAGEMENT

Work package objectives

- To update members with the progress in each work package
- To enable project cohesion and promote co-operation between partners
- To monitor project progress in completing tasks and achieving deliverables & milestones
- To ensure that all the EC's reporting requirements are met
- To establish effective communications media to facilitate contact between project partners, including a project web site
- To strengthen and develop links between partners to pave the way for future consortium expansion.

Period 1: Progress towards objectives

Task 5.1 Project co-ordination
Co-ordination has been led by the project co-ordinator, VIVID, through regular e-mail/phone conversations, but also through project meetings. There have been two formal meetings: one in Month 1 in Amsterdam, The Netherlands (M1); and a second in Month 6 at Chalmers University, Sweden. Minutes for these events are available from the MONARCH web site (http://www.monarchproject.org) and these minutes form contractual deliverables D3 and D6. Both meetings were highly successful from a coordination and technical standpoint. In addition, an informal meeting was held in London, in Month 9. Minutes are again available from the MONARCH web site.

The other main activity in Task 5.1 has been the conclusion of the consortium agreement. This document serves as a complement to the contract and its annexes and underlines and clarifies key agreements, such as the ownership of IPR, dispute resolution, management structures, *etc*. The consortium agreement (D1) was signed by all partners before the signature of the contract by the co-ordinator.

This document forms D8, the first periodic report of the project.

Task 5.2 Communication
The MONARCH web site went online in Month 3. This site is functioning well as an information source for the project. The web site currently has a very limited public area, which is intended be expanded as part of the dissemination work in the second half of the project. There is also a password-protected members' area, in which all project documents and deliverables are kept. This area includes an actions list, all the project deliverables and a "Progress" page, in which all the results and work associated with each work package is filed.

Log-in details are as follows:

MONARCH webpage: http://www.monarchproject.org
User name: p37441051-3
Password: apricot17

Period 2: Progress towards objectives

Starting point of work at beginning of reporting period

- Password protected website online and utilised by members
- Confidential blog set up for internal communication
- Project coordination running well.

Task 5.1 Project co-ordination

Project extension (Amendment No. 1)

Due to the difficulties in chip delivery, a project extension was requested and granted, and a revised Description of Work produced (October 2008).

Coordination methods

Co-ordination has been led by the project co-ordinator, VIVID, through regular e-mail/phone conversations, but also through project meetings. Due to the difficult technical coordination, additional planning meetings were held which greatly benefited the work coordination

- 18M review (Chalmers)
- 21M (Rome)
- 24M (Chalmers)
- 27M (Salford)
- 30M (Chalmers).

Minutes for these events are available from the MONARCH web site (http://www.monarchproject.org) and some of these minutes form contractual deliverables D20 and D25 and D31. All meetings were highly successful from a coordination and technical standpoint.

Several methods were tried to keep track of this complicated and fast-moving project:

- Confidential blog: This was in place at the beginning of the reporting period, but was found not to be a useful tool and it was not used much in the project
- Online Gantt charts, updated according to project progress were also tried, but this was rather cumbersome and inefficient
- WP leader monthly reports: Although there was a desire not to over-burden the team with reporting, a formal template for WP leader reports was used and monthly progress reports were sent diligently. These are used to direct activity and archived on the project website. This proved to be an extremely efficient and effective assistance to the coordination
- Actions register: From M6 of the project a formal detailed actions register was maintained by Vivid and used by all the partners. This was kept on the website. The final register is reproduced in the following section, to give an idea of the extent of activity within the project.

Task 5.2 Communication

The MONARCH web site went online in Month 3. This site functioned very well as an information source for the project. The web site public area was also expanded in the second reporting period. The main site is a password-protected members' area, in which all project documents and deliverables are kept. This area includes an actions list, all the project deliverables and a "Progress" page, in which all the results and work associated with each work package is filed.

Deviations from the project work programme, and corrective actions taken/suggested
No deviations in this reporting period.

List of deliverables

No.	Deliverable Title	Due date	Date delivered/ expected
D1	Consortium agreement signed	Month 1	Month 1 (Delivered)
D3	Minutes of KO meeting	Month 3	Month 3 (Delivered)
D4	Project web site online	Month 3	Month 3 (Delivered)
D6	Minutes of 6M project meeting	Month 8	Month 8 (Delivered)
D8	Mid-term report & draft plan for using & disseminating knowledge	Month 14	Month 14 (Delivered)
D9	Minutes of 12M project meeting	Month 14	Month 13 (Delivered)
D20	Minutes of 18M project meeting	Month 20	Month 18 (Delivered)
D24	Final Report and PUDK	Month 30	Month 33 (Delivered)
D25	Minutes of final project meeting	Month 30	Month 30 (Delivered)
D31	EXT Minutes of 24M project meeting	Month 26	Month 26 (Delivered)

List of milestones

There are no milestones in Work Package 5.

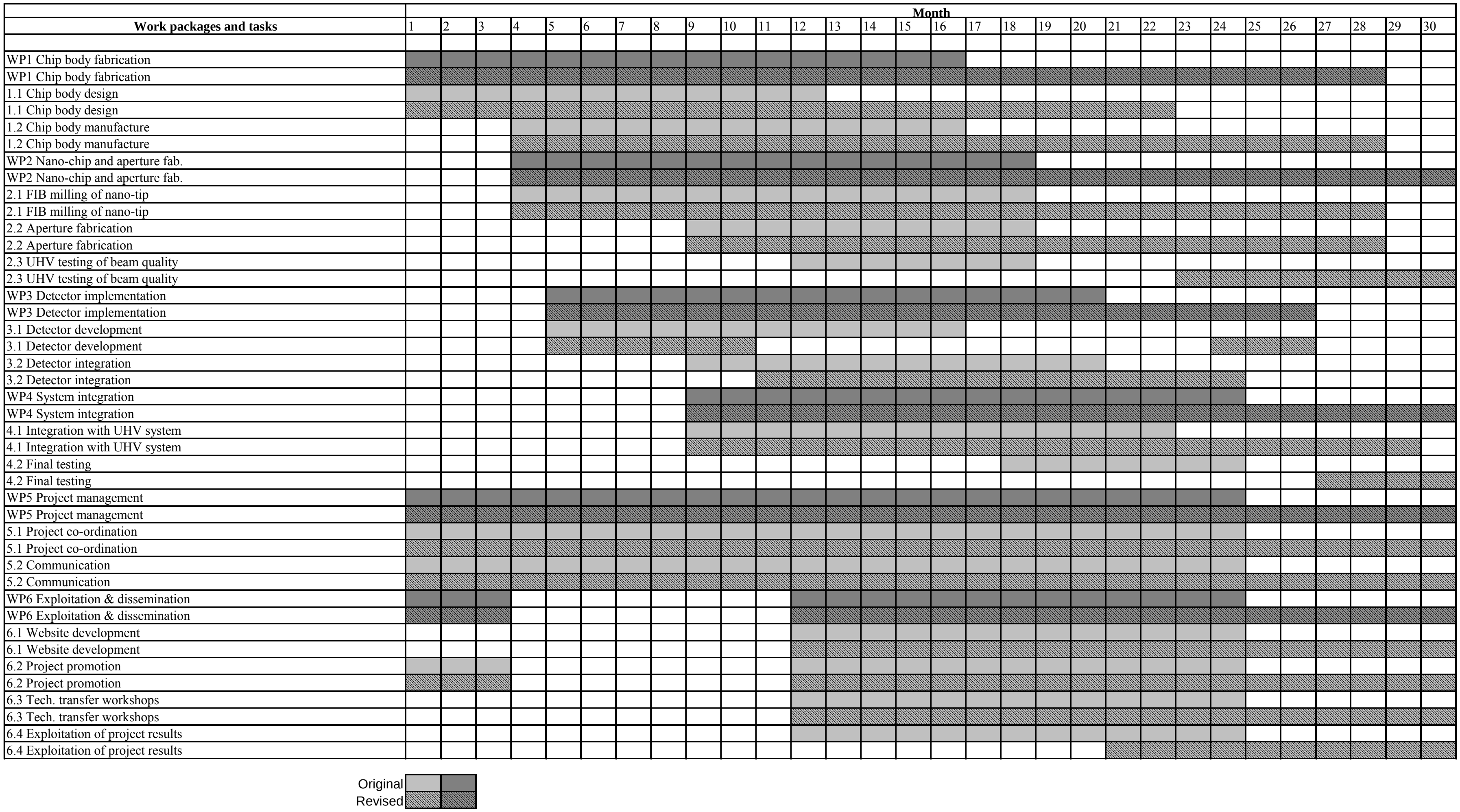
CONTRACTORS' PERFORMANCE

No changes have been made to the consortium. All contractors have performed their work diligently within the project. No problems have arisen and the entire consortium is satisfied with the progress in the project.

PROJECT TIMETABLE AND STATUS

No significant delays have occurred since the revised Description of Work (Oct-08). The front-lined bar chart on the following page shows a good reflection of how the project progressed in the second reporting period.

Front line Bar chart for Monarch



PROJECT CO-ORDINATION ACTIVITIES

Most of the project's co-ordination activities have been described in previous sections. There have been project meetings in Months 1, 6, 9, 12, 18, 21, 24, 27 and 30. Partners have communicated regularly with one another. There have been a number of visits between partners to discuss the work and to work jointly. The geographical proximity of NFAB and Salford has permitted several meetings and particularly close joint technical work; similarly the Swedish partners and the Netherland partners (C2V and University of Twente).

Intra-consortium communication has been mainly *via* e-mail and phone calls. This has been found to work well. However to aid this, several methods were tried to keep track of this complicated and fast-moving project:

- Confidential blog: www.monarchproject.wordpress.com. This was in place at the beginning of the reporting period, but was found not to be a useful tool and it was not used much in the project
- Online Gantt charts: were not popular with the consortium
- WP leader monthly reports: Although there was a desire not to over-burden the team with reporting, a formal template for WP leader reports was used and monthly progress reports were sent diligently. These are used to direct activity and archived on the project website. This proved to be an extremely efficient and effective assistance to the coordination.

There have been no collaborations with other projects or programmes, although the consortium is open to such links should the opportunity arise. However, there is considerable caution regarding release of information since this is a highly sensitive commercial topic.

Actions register: From the beginning of the project a detailed actions register was maintained and used by all the partners. This was kept on the website. The final register is reproduced on the following page, to give an idea of the extent of activity and cooperation within the project.

MONARCH ACTIONS REGISTER

Open actions

No.	Detail	Member	Opened	Due	Closed	Comments
12M-11	Investigate vehicles for further Monarch-related work	*Vivid*	21-Jan-08			Ongoing
27M-7	Super-tip development work	NFAB	19-Mar-09			Not achieved in timescale of project
27M-8	Investigate potential for paper on tip sharpening technique	Chalmers	19-Mar-09			Ongoing
27M-23	Get interview amended and online	SAL	19-Mar-09			Not achieved in timescale of project
30M-2	Suggest potential workshop events in next 6-18M	Chalmers/Salford	25-Jun-09			Not achieved in timescale of project

Closed actions

No.	Detail	Member	Opened	Due	Closed	Comments
30M-1	Send deliverables cover sheet	Vivid	25-Jun-09		Jun-09	
30M-2						
30M-3	Submit abstract to COMS	NFAB	25-Jun-09			Missed deadline
30M-4	Send details on intended MonarCh publications	Chalmers	25-Jun-09		Jun-09	
30M-5	Discuss chip problem with C2V and identify cause	MESA+/C2V/ Chalmers	25-Jun-09		Aug-09	See D12 Appendix
30M-6	Add Anke & Ihab as authors on JPL paper	NFAB	25-Jun-09		Jul-09	Request submitted
30M-7	Specify follow-ups from SPIE meeting and paper	NFAB	25-Jun-09		Jul-09	
30M-8	Request reporting extension from EC	Vivid	25-Jun-09		Jul-09	45 days granted
30M-9	Request meeting with PO to present project progress	Vivid	25-Jun-09			PO response: meeting not required
27M-1	Try to obtain Cambridge chip bodies and detailed specification	NFAB	19-Mar-09			No success
27M-2	Continue to ask SMC (Edinburgh) for chip bodies	NFAB	19-Mar-09			No success
27M-3	Manufacture and install flight tube mounting brackets (by 27-Mar-09)	NFAB	19-Mar-09			N/A: emission obtained without flight tube

27M-4	Plot I-V curves from CNT	NFAB	19-Mar-09		Jun-09	Done by Chalmers: see D15
27M-5	Demonstrate beam through 2μm aperture (by 17-Apr-09)	NFAB	19-Mar-09			Complete: see report Mar-09
27M-6	Agree SAL visit date to carry out beam characterisation work	Chalmers	19-Mar-09		20-Mar-09	Noise reduced and performed field emission from CNT onto a flat substrate
27M-7						
27M-8						
27M-9	Investigate methods of ensuring electrode contact (& check with MESA+)	Chalmers	19-Mar-09		Jun-09	Not relevant: chip problems
27M-10	Measure conductivity of TEOS electrodes	Chalmers/SAL	19-Mar-09			Not relevant: chip problems
27M-11	Send photo of apparatus with annotations	Chalmers	19-Mar-09		27-Apr-09	
27M-12	Check on 40% RTD spend with EC	Vivid	19-Mar-09		19-May-09	Guideline only (PO to confirm)
27M-13	Send latest spend info with forecast to project end	ALL	19-Mar-09		16-Apr-09	Vivid sent final forecast 16-Apr-09
27M-14	Combine forecasts and check OK	Vivid	19-Mar-09			OK
27M-15	Contact new PO to give update on project and request permission for chip set & control system	Vivid	19-Mar-09		27-May-09	Update given. Info rqd from NFAB re chipset & Salford re control
27M-16	Send template of report to all partners	Vivid	19-Mar-09		28-Apr-09	
27M-17	Doodle poll for final meeting date	Vivid	19-Mar-09			25-Jun-09 Gothenburg; email sent 16-Apr-09
27M-18	Develop new "thick" chip design	NFAB	19-Mar-09		May-09	Complete
27M-19	D21 Sales brochure	NFAB/Vivid	19-Mar-09		May-09	
27M-20	Contact PO to try to re-define D27. Publication? Website?	Vivid	19-Mar-09			Should be OK (PO to confirm)
27M-21	Put (approved) Monarch info on Salford Microscopy website	SAL	19-Mar-09		22-Jun-09	Online (here) 22-Jun-09
27M-22	Put Monarch info (from SAL) on website	Chalmers	19-Mar-09		01-Jun-09	Online
27M-23						

27M-24	Consider strengthening first workshop material	Vivid	19-Mar-09			Combine with D27 collated "Disseination activity"
27M-25	Ask MESA+ re. paper/ dissemination *e.g.* stress	Vivid	19-Mar-09			MESA+ consider not appropriate for paper
24M-1	Ron Petersen to contact Andy Matthews at Cambridge and pass on info to group	NFAB	22-Jan-09		23-Feb-09	
24M-2	Write D16 and submit as formal deliverable	SAL	22-Jan-09		06-May-09	
24M-3	Consider scope for papers on very small emitters	All	22-Jan-09			Not realistic in project timescale
24M-4	Phil Edmondson to contact Edinburgh and confirm plans for final chip bodies	NFAB	22-Jan-09			Updated 27M-2
24M-5	Prepare itemised payment by date to calculate spend to date	All	22-Jan-09			In progress
24M-6	Get formal approval from consortium for further payment	Vivid	22-Jan-09		10-Feb-09	
24M-7	Circulate SPIE paper for approval	NFAB	22-Jan-09			No time for approval
24M-8	Confirm FP6 acknowledgement requirements for publications etc.	Vivid	22-Jan-09		13-Feb-09	
24M-9	Send list of recent patent applications to Vivid	NFAB	22-Jan-09			
24M-10	Update Gantt chart and send to Vivid	All	22-Jan-09			OK
24M-11	Investigate possibility of obtaining power supplies from within university	SAL	22-Jan-09		03-Mar-09	Power supplies sourced for use with Nanofactory electronics. Single power supply sourced for use for PoC.
24M-12	Consider whether resource can be found for a third iteration of the Cambridge chips	All	22-Jan-09			N/A
24M-13	Circulate C2V/MESA+ chip design drawings	Chalmers	22-Jan-09		27-Apr-09	Complete
21M-1	Confirm details of chip design, particularly aperture diameter	NFAB	26-Sep-08			See M24-13

21M-2	Demo of supertips by Month 24 (Xmas 08)	SAL	26-Sep-08			On hold. Super-tip fabrication will continue after testing of CNTs with MESA+ chips. Fabrication rig has been constructed. Replaced by M27-7
21M-3	Ensure Andrew Bleloch is integral part of supertip demo	NFAB	26-Sep-08			Dr. Bleloch actively involved
21M-4	Produce Fowler-Nordheim plots to estimate emitter area of CNTs	SAL	26-Sep-08		Jun-09	Done by Chalmers: see D15
21M-5	Discuss reduction of payment to SMC (Edinburgh) due to slow delivery and poor quality results	SAL	26-Sep-08		Oct-08	Teleconference held 9/10/08 between Salford and SMC: 15% discount agreed
21M-6	Consider old Edinburgh chips and earlier MESA+ chips using the low voltage negative focusing mode (-76V may be operable?)	SAL	26-Sep-08		Dec-08	Use of low voltage mode will be trialled alongside high voltage focussing mode.
21M-7	Send details of “Nano” magazine publication and Frost & Sullivan article	NFAB	26-Sep-08		21-Mar-09	
21M-8	Use Oct-08 conference as dissemination event if appropriate	Nfac	26-Sep-08			In-situ TEM methods; not appropriate
21M-9	Contact Kelvin Nanotech and inform them that the work is postponed indefinitely	SAL	26-Sep-08		Nov-08	Complete
21M-10	Discuss methods of reducing cost on electronics “shopping list” through use of borrowed kit, simplification, compromise	SAL/ Chalmers/ Nfac	26-Sep-08			Complete: reduced by c. 50%: see Johan Angenete email 16-Oct-08
21M-11	Send Vivid detailed spend to date and budget forecast, with comments on what may be added from Cambridge chips and/or electronics	SAL	26-Sep-08		16-Oct-08	Discussions complete; see shopping list

21M-12	Send Vivid detailed spend to date and budget forecast, with comments on what may be added for electronics	Chalmers	26-Sep-08	19-Jan-09		Rcvd, but dependent on exchange rate
21M-13	Place order on Cambridge for new chips; NB discuss pricing for extra chip sets (i.e. >5pc)	NFAB/SAL	26-Sep-08		Nov-08	Order placed
21M-14	Send all members the SIMION calculations for various designs to date	NFAB	26-Sep-08			Complete
21M-15	Discuss low current and drive electronics requirements for new chips with Cambridge	NFAB/SAL	26-Sep-08		02-Mar-09	N/A Cambridge order cancelled
21M-16	FIB drilling trials (see Gantt chart)	SAL	26-Sep-08		Nov-08	<u>Complete: reported in Dec prog report</u>
21M-17	FIB & HF etch trials (see Gantt chart)	Chalmers	26-Sep-08		11-Dec-08	<u>Trials complete. Technical report submitted</u>
Q18-1	SIMION and LORENTZ models of current MESA+ chip body with the pair of problematic input electrodes shorted	<u>*SAL/MESA+/ Chalmers*</u>	23-May-08		07 & 14-Jun-08	Chalmers models sent out 07 & 14-Jun-08. Simulations show it is possible to use the chip body (two elements short circuited) as a three-element extractor and lens
Q18-2	Add EU flag and FP6 logo to poster and brochures (D21)	<u>*NFAB*</u>	23-May-08		Jun-08	Closed
Q18-3	Make new video for YouTube and SAL websites	<u>*SAL*</u>	23-May-08			Recorded 12-Dec-08. Too technical; update in progress Apr-09. Updated with 27M-23
Q18-4	Send list of relevant trade shows and conferences to Vivid	<u>*ALL*</u>	23-May-08			OK
Q18-5	Organise workshop (D18) on microscopy at SAL (Andrew Bleloch closing lecture)	<u>*SAL/NFAB*</u>	23-May-08		18-20 Jun-08	Held at Salford 18-20 June 2008
Q18-6	Select new chip body design build method with input from consortium	<u>*NFAB*</u>	23-May-08		Aug-08	Complete (Cambridge)

Q18-7	Obtain pricing and timing for delivery of new chip body design fabricated by external source	*NFAB*	23-May-08		08-Sep-08	Complete (Cambridge Nanoscience)
Q18-8	Send Al electrode samples to Chalmers (some with FIBed holes) for electrode evaluation	*SAL*	23-May-08		N/A	Change of plan re. chip bodies
Q18-9	Liaise re. adaptor plate for smaller chips	*SAL/ NFAC*			23-May-08	Adaptor drawings sent
Q18-10	Prepare extension proposal	*VIVID*	23-May-08		30-Oct-08	In progress
Q18-11	Send short paragraph to NFAB summarising the potential for the project for inclusion in New Scientist article	*ALL*	23-May-08		13-Jun-08	Article appeared 13-Jun-08
Q18-12	Continue with single sided chip body design	*MESA+*	23-May-08			Complete: samples delivered at 21M meeting
Q18-13	Send new Edinburgh chips to Chalmers	*SAL*	23-May-08		N/A	Change of plan re. chip bodies
Q18-14	Send nano-positioners to SAL	*NFAC*	23-May-08		22-Aug-08	
Q18-15	Send carbon nanotube tips to SAL ASAP	*Chalmers*	23-May-08		26-Aug-08	Complete
Q18-16	Print brochure (D21) and send to partners	*NFAB*	23-May-08			Handed out at 21M meeting
Q18-17	Supply detailed chip geometry for modelling	*MESA+*	23-May-08			OK
Q18-18	FIB one of the existing MESA+ wafers and drill apertures to check effect of PtIr tip near aperture	*Chalmers*	23-May-08		01-Dec-08	This work will be carried out on processed chips in 21M-17
Q18-19	Dice and expose existing MESA+ wafer and send to SAL for FIB and testing using crude electrode connection	*C2V*	23-May-08		Jun-08	Complete
Q18-20	Agree schedule for lithography for next project period	*NFAB/C2V*	23-May-08			OK
Q18-21	Send latest spend to date and forecast information	*ALL*	23-May-08			See 24M-5
12M-01	Order adaptor plates for 3x3mm^2 chip bodies	*SAL*	21-Jan-08		N/A	Adapter plates not rqd: Cambridge to provide chip with electrical contacts
12M-02	Send nanopositioner to SAL by 20-Feb-08	*NFAC*	21-Jan-08		26-Aug-08	Completed

12M-03	Send engineering drawing of nanopositioning apparatus showing electrical contact positions	NFAC	21-Jan-08		05-Mar-08	
12M-04	Register on Wordpress for blog access	All	21-Jan-08		Various	
12M-05	Send text to Vivid on "snapshot" of WP	WP leaders	21-Jan-08			Monthly
12M-06	Circulate paper for contact info	*NFAB*	21-Jan-08		Aug-08	Paper has been circulated and submitted to JAP
12M-07	Circulate editable version of poster	NFAB	21-Jan-08		20-May-08	
12M-08	Exhibit poster at appropriate exhibitions	*NFAC*	21-Jan-08		N/A	Covered by Q18-4
12M-09	Investigate potential for exhibitions	*C2V*	21-Jan-08		N/A	Covered by Q18-4
12M-10	Compose membrane stress paper and circulate for comment	*MESA+*	21-Jan-08		18-May-09	Insufficient breadth for paper
12M-11						
12M-12	Send W/Ti coated multi-layer chips to Chalmers by wk 5 2008	*SAL*	21-Jan-08			W/Ti multi-layers sent to Chalmers
12M-13	Manufacture samples of 2nm layers of W, Pt, Au and Al onto polysilicon substrates and send to Chalmers by wk 6 2008	MESA+	21-Jan-08			Samples sent
12M-14	Perform low energy electron beam stability testing of SAL and MESA+ samples	*Chalmers*	21-Jan-08		26-Sep-08	Results presented at 21M meeting
Q9-1	Dr. Bleloch to visit Chalmers to advise on nano-tip fabrication	*NFAB*	03-Sep-07			N/A: Chalmers to work on CNT tips
Q9-2	Increase conductor cover around aperture on chip body	*MESA+/C2V*	03-Sep-07			Discussed at 18M meeting
Q9-3	Poly-Si conductivity testing	*MESA+/C2V*	03-Sep-07			Tested: pass!
Q9-4	Send chip body samples to NFac (gold covered if low conductivity)	*MESA+/C2V*	03-Sep-07		24-Oct-07	Au layer, not poly-Si
Q9-5	Confirm dimensions of positioning system to permit holder design	*Nfac/ SAL*	03-Sep-07		19-Nov-07	
Q9-6	Discuss SiO2 on Si substrate system	*MESA+/ SAL*	03-Sep-07	30-Nov-07		
Q9-7	Compose bullet-point history of material choice (W, Au, Al)	*SAL*	03-Sep-07		21-Nov-07	Closed
Q9-8	Continue with emitter and detector selection	*Chalmers*	03-Sep-07		06-Nov-07	Channel plate
Q9-9	Order chip bodies from	*SAL*	03-Sep-07		07-Nov-07	

	Edinburgh					
Q9-10	Send blank chip bodies to Chalmers for nano-positioning trials	*SAL*	03-Sep-07		N/A	Blank chip bodies to be sent to Chalmers direct from MESA+
Q9-11	Send chip design to Salford to analyse beam optics and edge effects	*MESA+/C2V*	03-Sep-07			Design sent
Q9-12	Survey of IPR on nano-pyramids	*Nfac*	03-Sep-07		07-Nov-07	
Q9-13	Dr. Bleloch to advise Salford and Chalmers on nano-tip fabrication	*NFAB*	03-Sep-07			
Q9-14	Prepare summary document of heating methods (resistive, laser)	*Nfac/SAL/ NFAB*	03-Sep-07		N/A	No longer relevant
Q9-15	Send information on column manufacturers to Nfac	*Gatan*	03-Sep-07		N/A	No longer relevant
Q9-16	Look into a blog function on the Monarch website	*Vivid/NFAB*	03-Sep-07		16-Jan-08	Blog online 16-01-08
Q9-17	Modify poster for website public area	*NFAB*	03-Sep-07		20-May-08	
Q9-18	Send details of competition	*SAL*	03-Sep-07	30-Nov-07		Not deemed relevant (SAL)
6M-01	Retest compressive strength of TEOS oxide membrane	MESA+/C2V	31-May-07	30-Sep-07	21-Jan-08	Reported at annual meeting
6M-02	Retest conductivity of Si-rich nitride	MESA+/C2V	31-May-07	30-Sep-07	21-Jan-08	Reported at annual meeting
6M-03	Test sandwich layer strength, lithography and FIB testing	MESA+/C2V	31-May-07	30-Sep-07	21-Jan-08	Reported at annual meeting
6M-04	Consider in-house FIB for internal and MESA+ wafers	*Chalmers*	31-May-07	30-Sep-07	09-Nov-07	Good results
6M-05	Complete characterisation of tungsten nanotip CVD deposition and material	*Salford*	31-May-07			SAL moved onto etched tips
6M-06	Send Gantt chart of project for respective WP	*WP leaders*	31-May-07	30-Sep-07	11-Nov-07	
6M-07	Produce test chips (1 µm of TEOS oxide; 200 nm of polysilicon as a sandwich; thin tungsten layer)	*MESA+*	01-Jun-07	30-Sep-07	24-Oct-07	Au layer, not poly-Si
6M-08	Form a range of aperture sizes in test chips using FIB	*Chalmers*	01-Jun-07	30-Sep-07	21-Jan-08	A range of good quality aperture sizes have been "FIBed" (reported at 12M meeting)

6M-09	Test chip structure in STM with a range of aperture sizes	*Chalmers*	01-Jun-07	30-Sep-07	21-Jan-08	Complete: test chip structure too flexible for stable field-emission; reported at 12M meeting
6M-10	Explore sources for supertips	*NFAB/Chalmers*	01-Jun-07	30-Aug-07	07-Nov-07	No commercial sources found
6M-11	Explore conventional nanotip formation	*NFAB/ Salford*	01-Jun-07	30-Aug-07	Aug-08	Conventional nanotips have routinely been fabricated using a KOH etchant
6M-12	Explore carbon nanotube tips	*Chalmers*	01-Jun-07	30-Aug-07		Field-emission demonstrated from CNT inside SEM against a surface of gold
6M-13	Circulate Gantt template (based on Salford format)	*Vivid*	01-Jun-07	30-Jun-07	26-Jun-07	
6M-14	Compile Gantt charts from WP leaders	*Vivid*	01-Jun-07	30-Jul-07	18-Nov-07	Implemented as webpages
6M-15	Compile and assess spend profile	*Vivid*	01-Jun-07	30-Jul-07	30-Aug-07	
6M-16	Circulate list of dates for the next meeting	*Vivid*	01-Jun-07	13-Jul-07	26-Jun-07	
6M-17	Circulate predicted project spend profile with breakdown by partner	*Vivid*	01-Jun-07	30-Aug-07	30-Jun-07	
6M-18	Circulate minutes for review	*Vivid*	01-Jun-07	30-Jun-07	26-Jun-07	

4 – OTHER ISSUES

There are no other issues to report. All partners worked well, effectively and efficiently. There has been a tremendous "team spirit" in the project, and the SMEs recognise the clear benefits they get from the RTD performers' activities.

ANNEX - DEVELOPMENT & IMPROVEMENT OF THE ORIGINAL DESIGN

The project Monarch was based on an original concept for a sub-miniature electron microscope which was made by NFAB sometime previous to the start of the collaboration in January 2006. Since then NFAB have continued to develop the design in response to various factors which include more detailed beam optics calculations, the awareness of the availability of atomic electron emitters and the results of the difficulties in manufacturing the device by MEMS techniques. This has led to a large improvement in both the capabilities of the design and the ease of manufacture. The design concept is shown below.

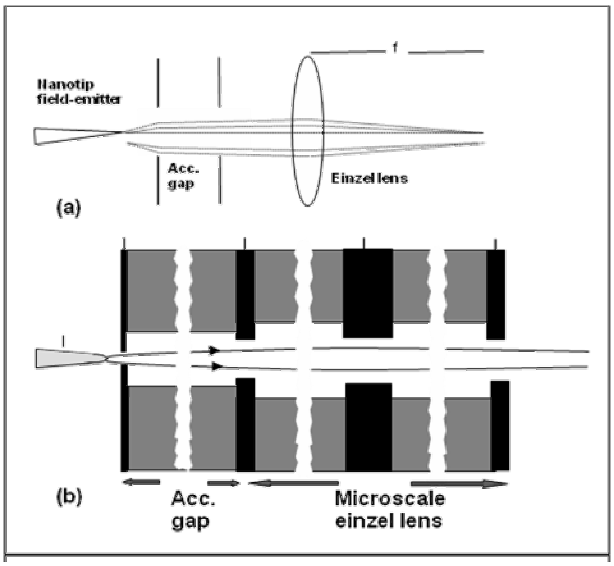


Figure 40 ***The original concept for the microscope consisted of a nanotip, electron source, an accelerating gap and a microscale, electrostatic lens. Electrons from the source are focused to a spot at a distance beyond the lens comparable to the length of the microscope. Because the system is extremely small the aberration are negligible and the microscope can image directly the nanotip and therefore its resolution is determined by the nanotip size.***

New designs

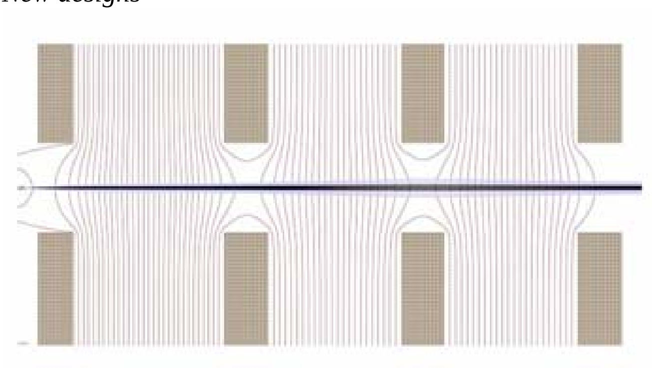


Figure 41 ***The design evolved into that shown above which uses an atomic emitter and so has an ultimate resolution of around 0.1nm. The electrodes which are preferably made from platinum are 1μm thick and the insulators (space between the electrodes) are 2μm thick. The aperture is 1μm. Note the thickness used in the calculations able is 0.5μm; little is changed if this is increased to 1μm but the construction is mechanically more sound.***

Further beam optical calculations resulted in the design shown above. This design is based on the availability of atomic emitters. Calculations show that it is possible to obtain a diffraction limited beam spot (λ=0.1nm) which is smaller than atomic dimensions if the microscope operates above 500eV. A most important parameter which is essential to the design is a knowledge of the field emission characteristics of the electron emitters. The programme of measurement has provided these vital emission characteristics. Broadly speaking we now know that a metal tungsten nanotip needs several thousand volts in isolation to emit in the nanoamp range and when placed at a micron distances from a surface will need hundreds of volts to emit. The measurements and beam optics showed that the initial accelerating gap shown above, has only a very small focussing effect so that the beam expands more and the aberrations of the lens are increased. In fact this has led to the design of **a microscope with a 10 micron sized** aperture so that the fill factor is small. The measurements have also been made on carbon nanotube emitters. These emit at a few hundred volts in isolation and around 10 volts when about 1 micron from a surface. These are suited to the original design since the effect of the entrance lens prevents the beam expanding more than around 100nm before entrance to the einzel lens. Even so the latest design is to increase the aperture to 2μm diameter. There are no problems in this respect with using atomic emitters.

The next effect we studied was the influence of stray charge on the insulator. As expected, this work revealed the well-known rule-of-thumb that the insulators had to be recessed by at least three times the separation of the electrodes if the beam is to be effectively screened from these stray charges. This does increase the difficulty of manufacture of the chips.
In order to make the manufacture as simple as possible we studied two options. Option one was to increase the thickness of the electrodes with a pro-rata increase in the aperture. Option two was to study the focussing effect of a system without an einzel lens, which consisted of just two electrodes separated by a single recessed insulator.

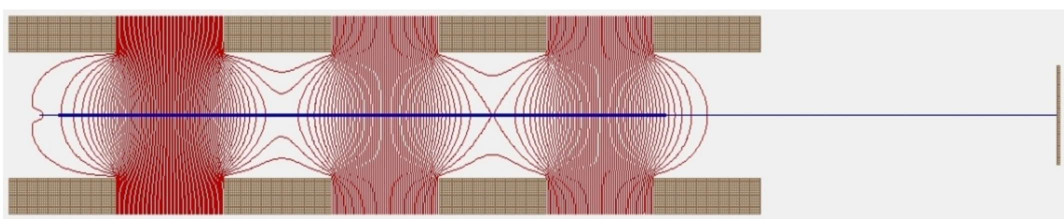


Figure 42 ***The manufacture is simplified and the voltage stress on the insulators is reduced if the insulators are increased to 10μm thickness and the aperture is increased to 10 μm. The ray trace above is for a carbon nanotube emitter. The performance is still diffraction limited to approximately the wavelength of the electrons if using an atomic emitter.***

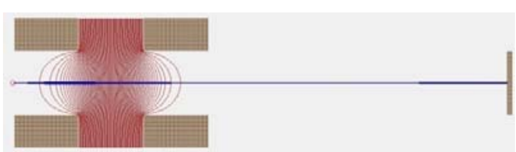


Figure 43 ***If a single atom emitter is used then the single accelerating structure consisting of two electrodes and one insulator has sufficient focussing power to be used as a microscope.***

What is important to understand is that the choice of emitter determines the design of the microscope and the important measurements of the emission characteristics from this CRAFT programme and from the scientific literature has made it possible to finalize a design which is easier to make and yet does not degrade the resolution. One of the important calculations of the resolution is shown below. The simple lesson is that making the microscope a factor 10 larger does not degrade the resolution because the overall size of the microscope and its focal length is still at approximately 100 times smaller than a conventional instrument so that the aberrations are still, on average, 100 times less.

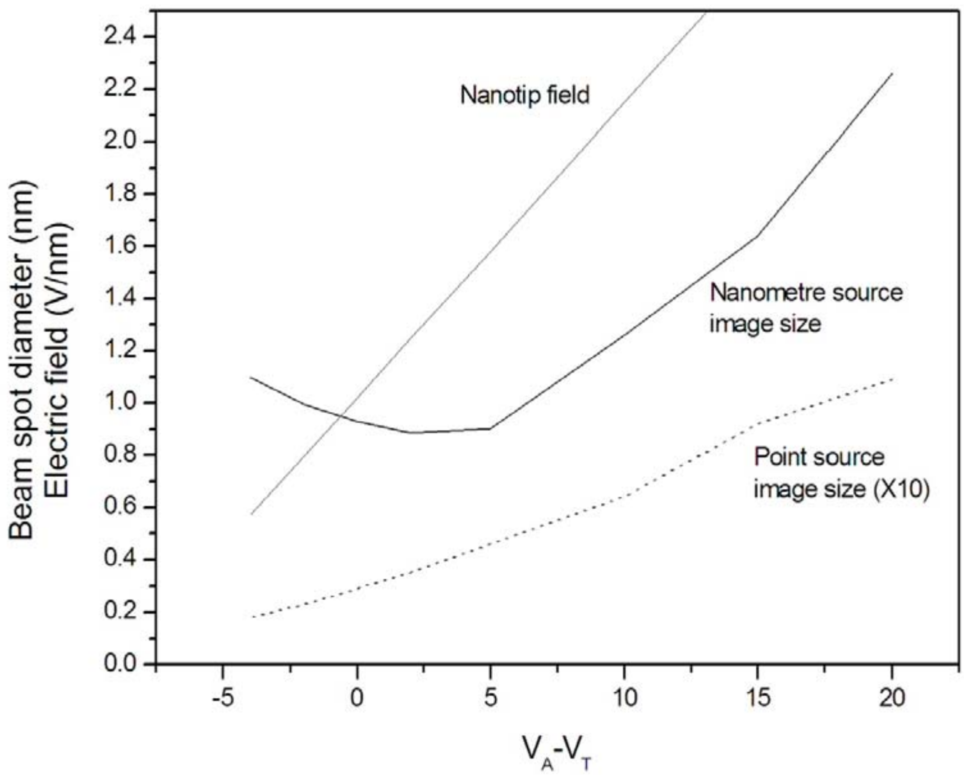


Figure 44 ***One of the many calculations made of the resolution of the instrument as a function of the nanotip field. The lesson is simple-the atomic emitters have the highest field and one can therefore obtain the best resolution from them.***

Overall Conclusions

The detailed calculations, including ray tracing, have been an ongoing programme throughout this CRAFT programme. They have shown that the design can be increased in size, including the aperture, without loss of resolution. This increase in size has led to a design which is more robust, is easier to manufacture and does not overstress the insulators.