An Excimer Laser Micromachining System for the production of Bioparticle Electromanipulation Devices.

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ABSTRACT

Multi-level micro-electrode structures have been produced using excimer laser ablation techniques to obtain devices for the electro-manipulation of bioparticles using travelling electric field dielectrophoresis effects. The system used to make these devices operates with a krypton fluoride excimer laser at a wavelength of 248nm and with a repetition rate of 100Hz. The laser illuminates a chrome-on-quartz mask which contains the patterns for the particular electrode structure being made. The mask s then imaged by a high-resolution lens onto the sample. Large areas of the mask pattern are transferred to the sample by using synchronized scanning of the mask and workpiece with sub-micron precision. Electrode structures with typical sizes of ~10μm are produced and a multi-level device is built up by ablation of electrode patterns and layering insulators.

To produce a travelling electric field suitable for the manipulation of bioparticles, a linear array of 10μm by 200μm micro-electrodes, placed at 20μm intervals, is used. The electric field is created by energising each electrode with a sinusoidal voltage 90° out of phase with that applied to the adjacent electrode. On exposure to the travelling electric field, bioparticles become electrically polarized and experience a linear force and so move along the length of the linear electrode array. The speed and direction of the particles is controlled by the magnitude and frequency of the energising signals. Such electromanipulation devices have potential uses in a wide range of biotechnological diagnostic and processing applications.

Details of the overall laser projection system will be presented together with data on the devices which have been manufactured so far.

Keywords: Excimer lasers, biosensors, micromachining.

1. INTRODUCTION

Diagnostic processes are becoming increasingly important in the modern chemical and biotechnological industries. Improved diagnostics enables manufacturing processes to be accurately controlled as well as allowing a wide range of routine testing to be carried out in an efficient and cost effective manner. This project is aimed at the development of

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microchip sized "biofactory" devices capable of performing a wide range of complex diagnostic tasks in a single, miniaturized, low-cost package. Biofactory devices have the advantage of being automated systems capable of the rapid analysis of small volume samples and so have applications in wide range of areas including medical and single-cell diagnostics, chemical detection and water quality control.

Using a combination of electrokinetic techniques such as Dielectrophoresis (the translational motion of particles in non-uniform AC or DC electric fields), Electrorotation (the rotational motion of particles in rotating AC electric fields) and Travelling Wave Dielectrophoresis (the translational motion of particles in travelling electric fields) particles can be spatially manipulated, and analysed in the biofactory devices([1]). The exact manner of a particle's motion depends on its dielectric properties and that of any medium it is suspended in. This dependence on dielectric properties allows biofactory devices to selectively manipulate particles within a sample by exploiting inherent differences in their dielectric properties or by the addition of markers, such as labelled antibodies, to modify the dielectric properties of the particles/antibody complex.

The "biofactory on a chip" concept adopts a modular design allowing devices to be rapidly developed for a wide range of applications. A key module is Travelling Wave Dielectrophoresis (TWD) Conveyor Tracks which are used to move particles between modules such as traps for collecting particles, junctions for separating sub-populations of particles and rotation chambers for the analysis of particles using electrorotation techniques. An example of a TWD conveyor track is shown in figure 1.

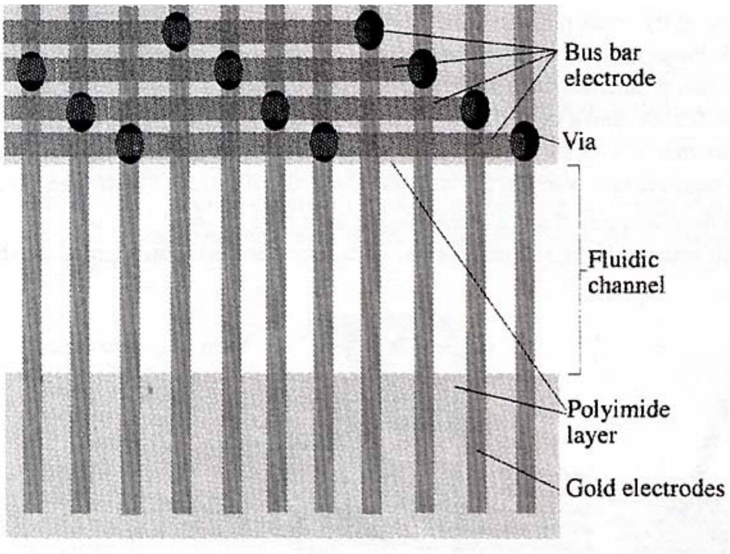


Figure 1

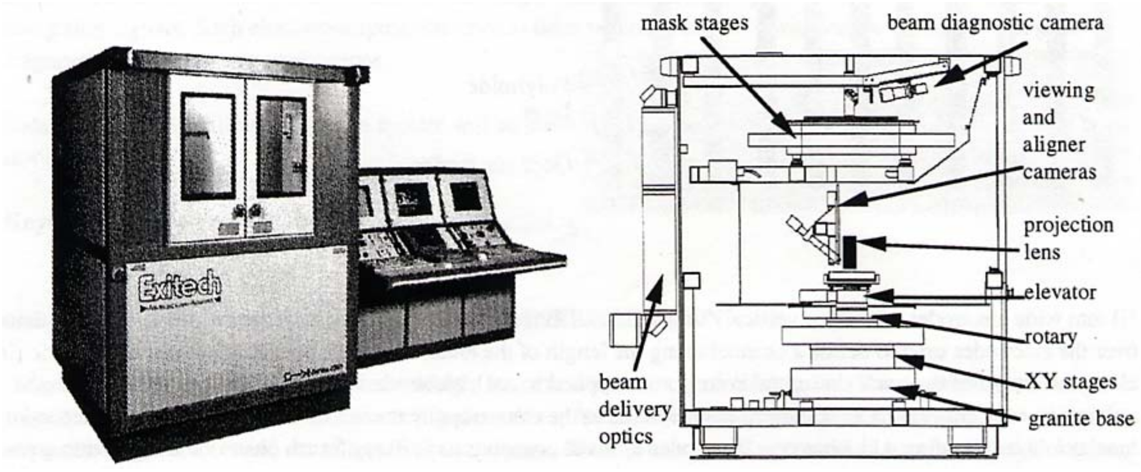
A diagram of a TWD conveyor track for the general movement of particles around a BFC device.

10 mm wide electrodes, shown as vertical "fingers", are fabricated on a insulating substrate with a second insulator over the electrodes used to define a channel along the length of the electrode track. To create a travelling electric field along the length of the track sinusoidal voltages are applied to each electrode which are 90° out of phase with the voltage on adjacent electrodes. Connections are made to the electrodes by the use of via-holes though the second insulator layer allowing 4 bus-bar type electrodes to make connections to every fourth electrode and providing just 4 external connections to the conveyor track module. By controlling the magnitude and frequency of the energising voltages, and hence the electric field, the speed and direction of the particles in the channel can be controlled allowing the bulk movement of particles between other biofactory modules whilst keeping the suspending medium stationary.

2. EXCIMER LASER PATTERNING SYSTEM

Due to the thin film nature of the biofactory modules excimer laser technology appears ideal for performing the majority of the fabrication steps involved in producing the devices([2]). Thin-metal films can be patterned directly by laser ablation without the need for the multi-step processes involved in photolithography (mask preparation, resist spinning, exposure, developing, etching and resist removal). Since the biofactory-on-a-chip concept utilizes modules it is possible to fabricate one chrome-on-quartz mask with all of the patterns necessary to manufacture each module, and "stitch" together each of the modules as required during the laser patterning step. The CNC system which controls the laser patterning tool can be programmed so as to index each of the mask patterns in the required sequence. In this way the layout of the biofactory circuit can be rapidly changed without the costly and timeconsuming effort of redesigning the mask. This technique is best suited to prototyping and small volume production: larger volume production would probably be better handled using more conventional photolithography batch processes.

The machine which is used to do this work is based on the Exitech Series 8000 patterning tool shown in fig. 2. A Lambda Physik Compex 110 krypton fluoride excimer laser operating at 248nm is mounted behind the tool. This laser produces a maximum output energy of 225mJ at 100Hz and gives a stabilized average power of 22.5 W. For this application, where fewer than 10 shots are typically required to pattern a single area of the thin-film, the laser is rarely used at its maximum repetition rate. The beam delivery system contains beam shaping and homogenization optics to create a uniform spot at the plane of a mask held on an open-frame CNC controlled X Y stage set. The beam homogenizer uses a double array system where each lens array has 6 x 6 (36) elements. The homogenizer produces 12 x 12 mm uniform illumination at the mask plane in which 80% of the pulse energy at the mask has an intensity variation of less than ±5% RMS. Projection lenses of various magnifications may be used to transfer the pattern of the mask onto the workpiece which is mounted on precision air-bearing X Y stages. For example one projection lens has a 10x demagnification, UNA, and a field size of 1.2 x 1.2mm (i.e. matched to the maximum spot size of the beam homogenizer). An alternative lens has 4x demagnification, 0.2 NA and 3 x 3mm field and can be used for coarser patterning. Maximum fluences achievable at the workpiece with the 10x and 4x lenses are 5.0 and 1.5 J/cm^2 respectively, and provided that the maximum fluence at the mask is kept at or below 0.1 J/cm^2, conventional chrome-on-quartz can be used without damage. These masks can be fabricated using standard mask-shop processes.



(a) (b)

Figure 2. The Excimer Laser Patterning tool (a) is shown in side-sectional view in (b). The laser (not shown) is behind the system enclosure.

The main XY stages are Aerotech Inca ATS80020 air-bearing stages using brushless linear servo motors giving 200 x 200mm motion travel. 0.1 µm resolution and ±2µm accuracy over their full travel. The open-frame mask stages are Aerotech Inc. ATS34030 also using brushless linear servo drive giving 300 x 300mm travel, 0.1µm resolution and ±5µm accuracy over their full travel. The mechanical mounting for the stages is critical for enabling the stages to meet their full performance specification, and the workstation enclosure and frame had to be carefully damped in order to reduce vibrational coupling between the mask and workpiece stage set. The encoders used on the workpiece and mask stages are Heidenhein linear glass scales. and the laser pattering tool is kept in a temperature controlled environment (±2°C typically) in order to reduce errors due to thermal expansion of the mechanical systems. An elevator stage with 5mm travel at 0.1um resolution and a diode laser-based height sensor system are used to maintain the workpiece at the correct height during processing. A rotation stage is incorporated into the workpiece stage set so that, when used with the vision-based off-axis aligner software. layer-by-layer registration can be achieved.

The stages are controlled by two Aerotech Inc. Unidex500 PC-based motion controllers, one of which is coupled to a laser firing card. The system can be used in step-and-repeat patterning for features on the workpiece which are smaller than the field of the lens, or in synchronized mask and workpiece scanning for patterning larger areas. Mask dragging mode is used for cutting fluid channels or removing unwanted insulating rcsist. These processing techniques have been described in another paper at this conference(3).

3. FABRICATION STEPS

3.1 Electrodes

Since the Biofactory on a chip concept is in its initial development stages there are a number of preliminary processes which have to be optimized before the biofactory modules can be produced. The first step which had to be developed was the fabrication of the base layer electrodes used to produce the travelling electric field. In order to verify that these electrodes could be manufactured and were suitable for producing the travelling electric fields, a simple planar electrode system was produced consisting of 20 individually energisable 5mm wide electrodes. These were configured to provide two individual conveyor tracks and an alternative channel based conveyor track as shown in figure 3.

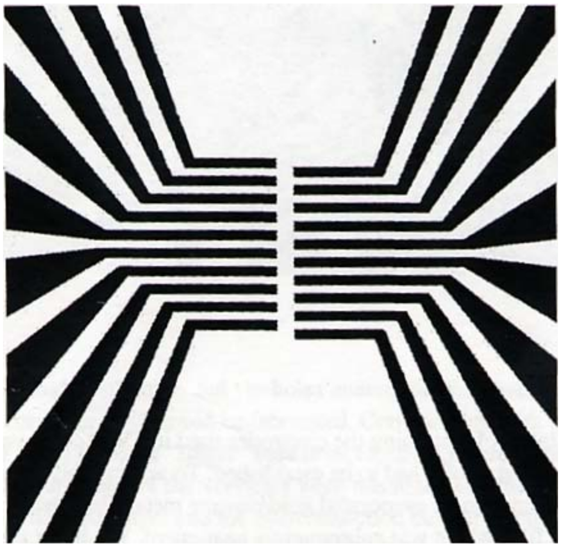


Figure 3 Planar electrode design for test TWD conveyor tracks using individually energisable electrodes

The substrate for the electrodes was either a glass microscope slide or a glass slide coated in a thin (3mm) layer of polyimide (DuPont) which had been cured at 350°C to produce a firm base. 1-5 nm of chrome was evaporated onto the substrate to act as a seed layer for a subsequently evaporated 70-100nm of gold. Patterning was achieved by a mask projection method using a chrome-on-quartz mask and the 4x imaging lens. The electrodes were formed in the gold/chrome metal layer by the single pulse removal of the unrequired metal using a wavelength of 248nm at a fluence of 200mJ/cm2. Examination of these electrodes revealed that, although the electrodes were suitable for use in TWD conveyor tracks, in some cases they lacked the achievable resolution and had a poor edge definition.

We have observed that the poor edge quality is associated critically with the quality of the deposited thin-film. In some evaporated metal films it has been impossible to ablate cuts of less than 7μm width, while the same optical system could achieve 2μm wide cuts in other films of similar thickness and of the same metal. Evaporated metal films, although simpler to apply, are particularly difficult to control whereas sputtered films generally have better reproducibility. An alternative technique employed to improve resolution and maintain edge definition was to coat the metal layer with a protective coating such as a photoresist. The resist was first patterned using 200 pulses at a fluence of approx. 100mJ/cm2, which is in agreement with previous work(4). This selectively removed the resist from the surface of the metal. Next a single pulse at 400mJ/cm2 was used to remove the exposed metal. Finally the resist was removed by rinsing in acetone. If required, residual photoresist was removed by exposing the electrodes to 100 pulses at 100mJ J/cm^2 using mask dragging as a cleaning technique. An example of these electrodes is shown in figure 4.

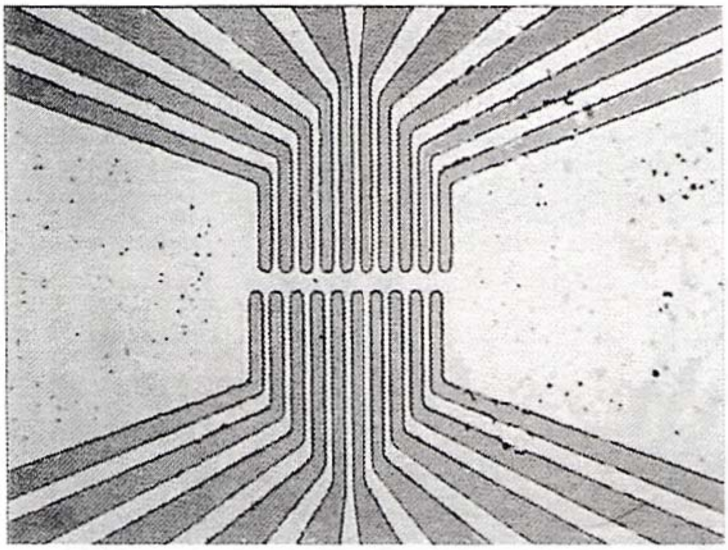


Figure 4.

An example of the laser patterned planar TWD conveyor track electrodes.

3.2 Vias

Having established the feasibility of patterning the electrodes used in TWD conveyor tracks a method of producing inter-layer connections through via-holes had to be established. To achieve this an array of electrodes ranging from 1604m to l 0um wide were formed in an evaporated gold/chrome metal film. Next the electrodes were spin-coated with an insulating polyimide film which was subsequently heat-cured. Via-holes were formed through the polyimide by projecting the image of a range of via-holes onto the insulator and exposing the polyimide at a wavelength of 248nm to 60 laser pulses at a fluence of IOOmJ/cm2, which is in agreement with previous work [e.g. 5], to selectively remove the exposed polyimide and reveal the gold surface of the underlying electrodes. Finally, a second set of electrodes were formed on the polyimide layer to form contacts through the insulator with the underlying electrodes. By measuring the electrical resistance between the upper and lower electrodes it was possible to determine if good electrical contact had been made.

The via-holes produced allowed contact to be made between the two layers. However, this connection method lacked the reproducibility required to produce electrode arrays typically requiring over 1000 individual through connections. Using electron microscope examination of the via-holes it was determined that the limitations in this method of producing via-holes resulted in poor coating of the sides of the via-holes and hence unreliable contact with the underlying electrodes. Due to the nature of the imaging optics employed in projecting a mask onto the surface of the insulator, the via-holes created by direct ablation of the polyimide possessed a wall angle of around 20°. By increasing this wall angle it was possible to produce a more reliable through connection. In tests it was decided to increase the angle to around 70°. To achieve this side wall angle the via-holes were machined with a series of steps. Having first produced a via-hole by the method already described the workpiece was moved by 1.4mm to one side of the via-hole and the workpiece was exposed to a further 8 pulses from the laser. Repeating this a further 6 times produces a wall profile consisting of 7 steps which, due to the original 20° angle of ablation tended to merge into one continuous slope. Repeating the process on the opposite side of the via-hole produced a reliable through connection as illustrated in figure 5.

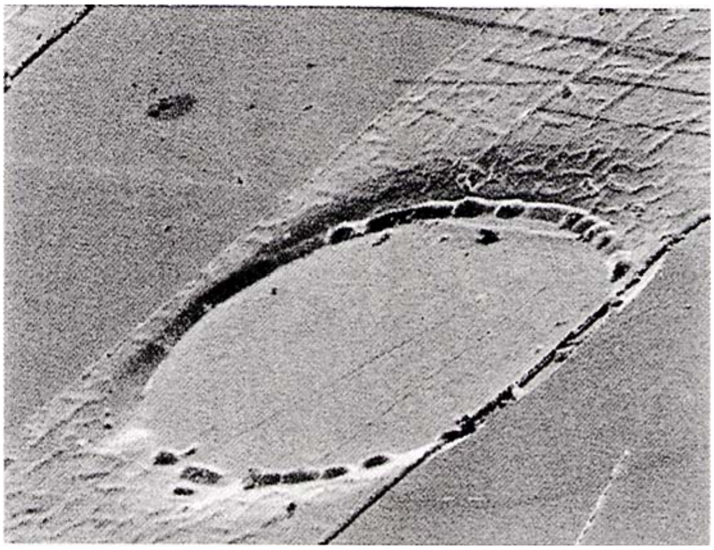


Figure 5. Electron Micrograph of a "shaped" via-hole showing the machined side to the hole where the top metal layer enters and leaves the hole. Just visible is the underlying electrode orthogonal to the top electrode.

3.3 Interconnection bus

Having verified that both the electrode patterning and via-holes interconnections were achievable using laser ablation techniques the complete TWD conveyor track could be fabricated. Commencing with a glass substrate coated in an evaporated gold/chrome bilayer metal film, the "finger" base level electrodes were patterned. Next the substrate was coated in a film of polyimide and cured before the via-holes were machined into the polyimide. Finally the device was coated in a second gold/chrome metal layer and the interconnection bus bar electrodes were patterned into the film. Since the external connection pads are large and have no real tolerance associated with them, simple photolithographic techniques could be used for their fabrication.

4. CONCLUSION

This series of experiments has demonstrated that both the electrodes and through connections required to produce large scale Biofactory devices are achievable using excimer laser ablation techniques. Following any slight modifications in the fabrication protocols which may become evident in testing the TWD conveyor track, the remaining modules of the biofactory can readily be developed. This in turn will lead to a prototype biofactory device directed in the first instance towards the analysis of parasites in potable water supplies.

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