Deep proton writing: a rapid prototyping polymer micro-fabrication tool for micro-optical modules

C Debaes1,3, J Van Erps1, M Vervaeke1, B Volckaerts1, H Ottevaere1, V Gomez1, P Vynck1, L Desmet1, R Krajewski2, Y Ishii1, A Hermanne1 and H Thienpont1

1 Department of Applied Physics and Photonics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Etterbeek, Belgium
2 Institute of Micromechanics and Photonics, Warsaw University of Technology, 8 Chodkiewicza St, 02-525 Warsaw, Poland
E-mail: christof.debaes@vub.ac.be

New Journal of Physics 8 (2006) 270
Received 2 September 2006
Published 13 November 2006
Online at http://www.njp.org/
doi:10.1088/1367-2630/8/11/270

Abstract. One of the important challenges to deploying the emerging breed of nanotechnology components is interfacing them with the external world, preferably accomplished with low-cost micro-optical devices. In our labs at the Vrije Universiteit Brussel (VUB), we are therefore focusing on the continuous development of a rapid prototyping technology for the fabrication of micro-optical modules. In this technology, which we call deep proton writing (DPW), we bombard polymer samples with swift protons, which will result after chemical processing steps in high quality micro-optical components. The strength of the DPW micro-machining technology is the ability to fabricate monolithic building blocks that include micro-optical and mechanical functionalities which can be precisely integrated into more complex photonic systems. The DPW technology is furthermore compatible with low-cost mass-replication techniques such as micro-injection moulding and hot embossing. In this paper we give an overview of the process steps of the technology and the characteristic qualities we can expect from the components made by DPW. The general overview of the technology is followed by three case studies of different micro-optical components that were fabricated at our labs: (i) two-dimensional fibre connectors, (ii) out-of-plane couplers for optical waveguides embedded in printed circuit boards (PCBs), (iii) intra multi-chip-module (MCM) level optical interconnection via free space optical modules.

3 Author to whom any correspondence should be addressed.
1. Introduction

Numerous technology advances during the last decades have revolutionized the fabrication of very small structures and components. This has brought plenty of innovation in existing markets and opened different unexplored market opportunities [1] such as bio-photonics, micro-fluidics and micro-sensors. With the current development of nanophotonics, the devices will be structured at the smallest of scales. With features below 100 nm these photonic components enter the realm where photonic, physical and chemical properties can be tailored to deliver unique device performances.

A well-established technology for fabricating small structures is the use of optical lithography. In this process a layer of photosensitive material is generally spin coated onto a substrate. This resist layer is subsequently patterned by exposing selected regions to light through a fine-structured mask by either projection lenses or direct contact methods. The absorption of light will affect the chemical structure and allows for a development of the exposed or unexposed areas. A number of techniques exists to transfer this pattern into the substrate: a selective growth of materials in the trenches of the resist, etching of the unprotected areas, or doping through the open areas of the resist by diffusion or implantation [2]. This optical lithography technique has matured enormously thanks to requirements in the micro-electronics area which is getting more demanding on each new technology node.

An often cited route to attain higher lithographic resolutions is the use of exposure beams with shorter wavelengths, leading to diminishing diffraction artefacts. This has led to the development of deep UV lithography ($\lambda_p = 183$ nm) which is now the standard technology to create the latest generation chips. For the next generation, extreme UV lithography [3] is regarded as a future alternative. For this technique the operating wavelength is typically 13.4 nm. At the extreme of optical lithographic techniques we find x-ray lithography that relies on x-rays with operating wavelengths in the range of 0.5–4 nm. With x-ray lithography, the nature of the exposing light is such that no material can be used to construct projection lenses, hence only shadow masks can be deployed.
Moreover, increasing attention is paid nowadays to lithographic techniques which rely on completely different physical processes. One approach is to use an exposure with electrically charged particles rather than photons. These methods rely on the extremely low associated wavelength of the charged particles, hence, they are in practical terms not limited by diffraction. The best known lithographic technique of this type is electron beam lithography [4]. It uses electron beams with energies of 1–100 keV and can routinely attain resolutions below 100 nm. Other approaches include focused ion lithography [5] (usually with Ga atoms), which exhibits, due to the higher particle mass, a smaller proximity effect than e-beam lithography, and electron projection lithography, which in principle can overcome the slow scanning speed of current e-beam lithographic techniques. Another approach that has the potential to become a low-cost alternative for the next generation lithographic steps is the use of nano-imprint lithography (NIL). In this technique, a rigid form is adopted to physically deform a heated coated polymer layer on top of a substrate [3, 6].

All the above techniques are focused however on patterning a flat surface with very fine features on a 2D plane as is required to create the different transistor parts in microelectronic circuits. Nevertheless, it is often desirable to fabricate more extensive 3D structures to fabricate micro-optical systems, integrated microsensors, micro-fluidic systems or medical devices. Therefore, new technologies are being investigated that are able to micro-structure deep geometries. Some of the tools that can be adopted for such a micro-fabrication step are: (i) laser photo-ablation, a method whereby a sample is exposed to such intense light pulses that some of the material at the surface is being spontaneously evaporated [7], (ii) the LIGA technology, a technique whereby a polymer substrate is exposed by a collimated beam of high-energy x-rays which penetrate deep into the substrate with negligible diffraction [8], (iii) stereolithography which is a novel approach to solidify selected regions from liquid photopolymers layer by layer using a scanning laser [9]. In addition, there exists a series of soft lithographic [10, 11] techniques to replicate patterns made with conventional lithography via moulding or stamping or by direct printing. The techniques can be applied to a range of substrates which can even be highly curved [12] to form 3D structures.

In this paper, we describe yet another technique for fabricating micro-optical modules, which we call deep proton writing (DPW). The special feature of this technology is that it can be adopted as a rapid prototyping technology to make micro-optical systems that can combine refractive micro-mechanical and micro-optical structures such as micro-holes, micro-lenses, micro-prisms and cylindrical micro-lenses. The paper is structured as follows. In section 2, we introduce the DPW technology and explain its major assets: the ion interaction, the irradiation process, the etching process and the swelling process by in-diffusion of monomers. An important aim of the DPW technology is to overcome the remaining micro-optical hurdles to massively introduce photonic interconnects in digital systems. In section 3, we explain our effort of building such components and describe different components that were made by the DPW technology: (i) two-dimensional (2D) single-mode fibre array connectors, (ii) out-of-plane couplers for optical waveguides embedded in printed circuit boards (PCBs), and (iii) intra multi-chip-module (MCM) level optical interconnections via free-space optical modules.

2. DPW as a micro-optical prototyping technology

At our labs we are optimizing a dedicated technology, DPW. Its concept finds its origin in the LIGA-technology (Lithografie, Galvanoformung und Abformung) [8] but differs in two
important aspects. Firstly, it is based on the use of protons rather than electromagnetic x-ray irradiation to shape polymer samples. Secondly, the DPW technology uses a direct write methodology as opposed to projection lithography which is adopted for the LIGA process where expensive masks are required for each new LIGA design. In fact, the thick masks required in the LIGA process are made in steps by repeating the LIGA process with a gradually higher energy until a mask with sufficient thickness can be electroplated. Both differences mean that the DPW process requires fewer infrastructural demands and has the potential of being a more flexible technology for rapid prototyping.

The basic concept of the DPW process is based on the fact that irradiating swift protons onto a polymethylmethacrylate (PMMA) sample featuring linear polymer chains (i.e. opposite of cross-linked) of high molecular mass, will rupture the long chains. As a consequence, the molar mass of the irradiated material will be reduced and free radicals will be created in the polymer, resulting in material properties that are very different from those of unexposed material.

Two different chemical steps were developed that can be applied to the proton bombarded areas. The first consists of etching the exposed area with a specific developer to produce micro-holes, micro-mirrors and micro-mechanical structures. The second process involves the in-diffusion of a MMA monomer to locally swell the irradiated zones. This will result in micro-spherical and micro-cylindrical lens surfaces (see figure 1). Both processes can be applied to the same sample after a single irradiation session as the dose required for the etching or swelling is very different.

It is obvious that with a total cycle time of about half a day per component and the required acceleration facilities, the DPW cannot be regarded as a mass fabrication technology as such. However, one of its assets is that it can be made compatible with low-cost replication techniques. Indeed, once the master component has been prototyped with DPW, a metal mould can be generated from the master by applying electroplating. After removal of the master, this metal mould can be used as a shim in a final microinjection moulding or hot embossing step [13].

Figure 1. Basic fabrication processes of deep lithography with protons. After a patterned irradiation we can either apply a binary chemical etching fluid to remove the irradiated regions or we can in-diffuse a monomer vapour to create micro-lenses through a swelling process.
2.1. Ion interactions

The kernel process of deep DPW is the exposure of selected regions of the sample to accelerated protons. In comparison to photolithographic techniques where the exposure is governed by electromagnetic radiation, the energy transfer of protons with their target material is fundamentally different. For UV-light lithography, the absorption of the beam is given by the well-known Lambert–Beer law which states that the fractional absorption is constant along the penetrating axis. This will result in an exponential decay of absorbed light quanta along their path. With x-ray lithography, the released energy at the absorption of a photon is higher than the binding energy. Hence, such an event can create, apart from inner shell transition, secondary free electrons through the photoelectric effect. These electrons with high kinetic energy are capable of locally breaking the long polymer chains.

In contrast, the charged particles in an ion irradiation, or more specifically a proton irradiation, will only travel to an energy dependent depth. Indeed, as the ions penetrate the substrate they gradually transfer energy to the host material mostly by interaction with the bonded electrons of the target material. This electric stopping power and associated range of ions in solids has been a domain of vigorous research since the discovery of energetic particle emission from radioactive materials. In 1913 Bohr established a model, based on classical mechanics, to describe ion stopping in matter [14, 15]. This was later refined to a quantum mechanical approach in 1930 by Bethe and Bloch [16]. Since then various scientists have contributed to the subject. Extended reviews can be found in [15], [17]–[19].

It turns out that the stopping power (the energy transfer per unit of penetration depth, $dE/dx$) is small at the early part of the ion trajectory. This energy transfer will gradually slow the swift ions down while their interaction density with the PMMA molecules is increasing. This will result in a maximum energy transfer and absorbed dose when the impinging ions have velocities equal to those of the electrons in the amorphous host material. Below this energy level, the ions’ energy transfer will decrease immediately and after a further penetration of some micrometres the ions will come to a complete stop. The resulting absorbed dose profile for proton irradiation can be found in figure 2. We can see that if we are using protons with an entrance energy of 8.3 MeV, the range is about 750 $\mu$m. This allows us to cut through the standard substrate thickness of 500 $\mu$m. During the penetration in PMMA, the protons will cause electron excitation and ionization of the molecular chains and thereby induce stresses inside the molecular chains [20]. These stresses result in a degradation of the irradiated PMMA-samples and make it possible to perform a selective chemical step. The reduced molar mass or molecular weight $M_{irr}$ after the absorption of a dose $D$ in J kg$^{-1}$ can be expressed as a function of the initial molecular weight $M_0$ ($=10^6$ g mol$^{-1}$):

$$\frac{1}{M_{irr}} = \frac{1}{M_0} + \frac{GD}{100eN_a},$$

(1)

where $e$ is the elementary charge unit and $N_a$ is Avogadro’s number. The factor $G$ is the yield for main chain scissions per absorbed energy of 100 eV. Detailed studies of the molecular mass before and after irradiation via gel permeation chromatography (GPC) and a micro-thermal analyser confirmed that the chain scission yield is equal to one [21]. The deposited dose $D$
Figure 2. 1D absorbed dose profile in PMMA after a proton irradiation of $1.2 \times 10^6$ particles $\mu$m$^{-2}$ for different entrance energies.

(in J kg$^{-1}$) is related to the incoming proton fluence $F$, i.e. the number of impinged protons per unit surface, and the stopping power of the swift protons in PMMA by

$$D = \frac{F}{\rho_{\text{PMMA}}} \frac{dE}{dx},$$

where $\rho_{\text{PMMA}}$ is the mass density of PMMA sample (1.19 g cm$^{-3}$).

Beside the gradual energy transfer of the protons to its amorphous host material, some spatial straggling of the impinging protons will occur while they are penetrating into the substrate. In contrast to the energy transfer, the straggling effects are primarily governed by multiple ion–ion (nuclear) interactions [21]. The straggling will result in a dose deposition slightly outside the targeted volume of the PMMA-layer and thus will decrease the steepness of the optical surfaces of the fabricated micro-structures after the etching process. We have developed an algorithm which can predict the 3D dose profile after a proton irradiation that includes both stopping power and the ion–ion scattering. In figure 3, we plot the resulting 2D absorbed dose profiles for a proton irradiation in PMMA through 100 $\mu$m pinhole collimator with entrance energies of 5.5, 8.3 and 11.5 MeV. We can see that within the first 500 $\mu$m, the dose widening due to straggling is a few microns for protons with 8.3 MeV entrance energy. Recently, we have started to use proton beams of 16.5 MeV to reduce the effect even further.

Conventionally, we would like to keep this straggling effect as small as possible to create deep optical surfaces with high aspect-ratio. However, in some cases we can use the straggling effect to our benefit. This is the case when fabricating conical shape fibre insertion holes to ease the fibre insertion. This will be explained more in detail in section 3.1.

2.2. The irradiation process

The proton beam used for developing micro-optical components is generated at the cyclotron facility of the Vrije Universiteit Brussel (VUB). The cyclotron (a CGR-MeV model 560...
Figure 3. The 2D absorbed dose profiles plotted for proton irradiation in PMMA with fluences of $3.2 \times 10^6$ particles $\mu$m$^{-2}$ for different entrance energies.

Figure 4. Schematic overview of the DPW irradiation set-up.

cyclotron) is capable of producing quasi-monoenergetic ($\Delta E/E = 1\%$) proton beams in the energy range between 3 and 45 MeV. The accelerated protons are transferred via a set of focusing quadruple magnetic lenses and switching magnets to the DPW set-up which is depicted in figure 4. In the figure the protons enter the irradiation vacuum chamber from the right-hand side.

In order to avoid beam scattering and energy loss of the protons along their trajectory, we perform all the irradiations under vacuum (pressure below $10^{-4}$ mbar). Depending on the settings of the focusing magnet coils, the proton beam will enter the set-up with a divergence of a few milliradians. From there, a set of collimators will reduce the beam to a pencil-like uniform beam with selectable diameters. First, a fixed water-cooled aluminium collimator reduces the diameter of the entering beam from a few centimetres to 2 mm. The second collimator is a 10 cm long aluminium block with a $1 \times 1$ mm$^2$ aperture hole. This design will restrict the divergence of the remaining proton beam and improves the beam pointing stability during irradiation. Part of this
block is machined to include a mechanical shutter driven by a small electromotor which can block the beam within a 1 ms timespan.

The final mask element is either 300 µm thick nickel stopping mask (fabricated with the LIGA technology) or a 500 µm thick tantalum mask (fabricated via electron discharge machining). The nickel mask contains different apertures with diameters ranging from 20 µm to 1 mm. By changing the position of the stopping mask, we can select different final proton beam sizes on the fly during one irradiation. The 300 µm mask is capable of stopping 8.3 MeV proton beams. With the 500 µm tantalum mask we are able to stop 16.5 MeV proton beams. The mask of this thickness only provides circular holes with a 170 µm diameter but allows us to fabricate components with steeper walls.

We position the PMMA sample in a metal holder that is mounted on a biaxial translation stage with a 50 nm accuracy over a total travel range of 25.4 mm. Because the initial proton energy is high enough to pass through 500 µm thick PMMA samples, they induce a charge in the measurement probe located directly behind the target. It is therefore possible to monitor the proton current and the total amount of particles hitting the sample by integrating the proton current during the irradiation. The proton measurement is based on a precision-switched integrator trans-impedance amplifier and its concept is averse to any fluctuations in the proton current caused by instabilities of the cyclotron [22]. It provides us with a measurement resolution better than 250 fC, which is two orders of magnitude smaller than the minimum proton charges required for our purposes. For a point irradiation the relation between the collected charge $Q$ and the proton fluence $F$ can be expressed as:

$$Q = eF \frac{\pi d^2}{4},$$

where $d$ is the aperture diameter.

Since PMMA is a positive resist the exposed area can be developed in a subsequent chemical step. This means that we have to irradiate the entire contour of the designed component. To create the contour, the PMMA sample is quasi-continuously translated perpendicularly to the beam with steps $\Delta x$ of 500 nm. At each step, the collected proton charge is measured at the measuring probe. If this value reaches the required proton charge, the microcontroller system will shift the sample to its new position one step away. The dose profile after a line diagram will not be uniform as it will be an overlap of different circular point irradiations. The peak proton fluence $F_{\text{max}}$ in this case will be:

$$F_{\text{max}} = \frac{4Q_{\text{step}}}{e\pi d \Delta x}.$$  

2.3. The etching process

As a next step, a selective etching solvent can be applied for the development of the irradiated regions. This allows for the fabrication of (2D arrays of) micro-holes, optically flat micro-mirrors and micro-prisms with high optical quality, as well as alignment features and mechanical support structures.

For the etching process, we make use of a GG developer (diethylene glycol monobutyl ether 60%, morpholine 20%, 2-aminoethanol 5%, and DI water 15%) as the etching solvent.
For standard components, etching lasts 1 h at an elevated temperature of 38°C. During the whole process the etching mixture is stirred by an ultrasonic stirrer. The etching is stopped by dipping the component in a stopping bath consisting of 20% water and 80% diethylene glycol monobutyl ether.

Following a study by Papanu [23], the dissolution or etching rate can be expressed as:

\[ v_{\text{etch}} = \frac{c_0}{(M_{irr})^n} \exp \left( -\frac{E_a}{kT} \right), \]

where \( c_0 \) and \( n \) and the activation energy \( E_a \) are system dependent parameters. Combining the above equation with equations (1) and (2), we get the following relation between the proton fluence and the etching rate (expressed in \( \mu \text{m s}^{-1} \))

\[ v_{\text{etch}} = c_0 \left( \frac{1}{M_0} + \frac{GF(dE/\rho_0 dx)}{100 eN_a} \right) \exp \left( -\frac{E_a}{kT} \right), \]

Fitting the above relation to experimentally obtained etching rates of irradiated zones, results in the following values: \( c_0 = 2.78 \times 10^{26}, E_a = 1.05 \text{ eV} \) and \( n = 2.9 \).

To get an insight into the limits of the flatness of the created surfaces, we need to make a distinction between the direction along and perpendicular to the proton trajectory. Along the proton trajectory the most important parameters that are affecting the surface flatness are the divergence of the incoming and the straggling of protons along their path by multiple ion interactions as described in 2.1. The flatness of surfaces in the direction perpendicular to the protons is limited by the precision on the movements of the translation stages (which have a closed loop accuracy of 50 nm). The roughness of the obtained surfaces is mainly determined by accuracy of the proton fluence measurement and the beam pointing stability.

Recently, we have optimized the surface quality of the etched surface after irradiation with our smallest nickel aperture of 20 \( \mu \text{m} \). With this proton beam size, an error in the position of the beam will be more pronounced and the signal-to-noise ratio of the measured proton current will be significantly smaller than with our standard 140 \( \mu \text{m} \) proton beam (as the proton current is 49 times smaller to obtain an equal proton fluence). Nevertheless, we succeeded in creating very high quality surface profiles even with this aperture [24]. In figure 5, the resulting local surface RMS roughness \( (R_q) \) and peak-to-valley flatness \( (R_t) \) are given. The graph shows the surface \( R_q \) and \( R_t \) as a function of the deposited particle charge per step. \( R_t \) was measured over a length of 500 \( \mu \text{m} \) along the proton trajectory and \( R_q \) was calculated by averaging several measurements over an area of 46 \( \mu \text{m} \times 60 \mu \text{m} \) with a non-contact optical profilometer (WYKO NT2000). From this graph, we can conclude that the best results are obtained when we irradiate the sample with a collected proton charge of 8 pC per step of 50 nm corresponding to a peak proton fluence of 6.4 \( \times 10^6 \) particles \( \mu \text{m} \)^{−2}. Figure 6 shows the profiles of the created surfaces. On the bottom graph the profile is shown in the direction of proton trajectory with a surface flatness \( R_t \) of 3.17 \( \mu \text{m} \). The top graph is a zoomed-in version of a profile perpendicular to the proton trajectory. The RMS roughness \( R_q \) interval of 27.5 nm is indicated on the graph as well. These results are on par with the surface roughness and the flatness results we are obtaining with larger apertures at the same entrance energies.
Figure 5. Surface roughness $R_q$ and flatness $R_t$ as a function of the deposited charge in each 0.5 $\mu$m step when using a 20 $\mu$m aperture.

Figure 6. Detailed plots for $R_q$ and $R_t$ at the charge collection of 8 pC per step of 500 nm.
2.4. The swelling process

The swelling process step will create spherical surfaces of the remaining irradiated zones which received a dose that was programmed to be too low for the etching. By exposing the sample to a controlled organic MMA vapour environment at an elevated temperature, the irradiated regions with a sufficiently low molecular weight will be receptive to an in-diffusion process of an organic monomer upon which their volume will expand. This way, irradiated regions with a circular footprint will be transformed into hemispherically shaped micro-lenses [25].

To swell the micro-lenses we are currently using a diffusion reactor which is brought to an elevated temperature of 70°C. After the stabilization of the temperature (within 0.2°C) MMA monomer is injected into the chamber such that it will create a saturated MMA vapour. The monomer vapour will now diffuse into the irradiated zones to create hemispherically shaped microlenses. After 40 min the sample is removed from the reactor and the in-diffused areas are stabilized by UV-illumination during 1 hr while keeping the temperature elevated at 70°C. The detailed physics behind technological processing steps have been published before [26]–[28]. We demonstrated that DPW is a flexible technology to fabricate 2D matrices of spherical microlenses with different diameters between 120 and 200 µm and focal numbers ranging from 1 to 7 on the same PMMA substrate. In figure 7(a) plane wave Mach–Zehnder interferogram is given of an array of spherical microlenses with a different lens sag (increasing from left to right).

We use an optical non-contact profilometer (WYKO NT2000) to measure the geometrical characteristics of the microlenses such as lens sag and lens diameter. For the optical characteristics we use a Mach–Zehnder interferometer constructed at the Erlangen Nürnberg University to measure the wave aberrations such as the point spread function (PSF), the strehl ratio and the modulation transfer function (MTF). A detailed comparative study of the obtained DPW
In figure 7(b) one can find the measured wave-aberration of a typical lens with a high focal number ($f = 7$). The measured lens aberration of this micro-lens has a rms value of $\lambda/5$ which is above the Maréchal criterion to obtain diffraction limited lenses ($\phi_{\text{RMS}} \leq \lambda/14$). We can conclude that although fabrication techniques exist that yield higher quality micro-lenses, the advantage of the DPW approach is that the lenses can be relatively fast prototyped and can be monolithically integrated in complex micro-systems.

Within large arrays of DPW micro-lenses, we typically obtain a uniformity of the lens sag of 0.3%. However, when the micro-lenses are brought in close proximity we need to account for a small and deterministic change in the lens sag. This can be easily compensated by giving the peripheral lenses of the array a slightly lower dose. For example, when micro-lenses with a diameter of 140 $\mu$m are created on an array with a 250 $\mu$m pitch, the peripheral lenses need a 3% lower dose to obtain the same lens sags over the whole array.

Our sample-to-sample repeatability is however much lower. Therefore, we have started a new set-up that will contain an in situ monitoring of the lens swelling behaviour during the swelling process [30].

3. Micro-optical components for board level optical interconnects

High-speed data links between digital processing units are currently under high pressure. It is indeed not unusual for present-day galvanic multi-gigabyte links to require compensation on the high-frequency components for as much as 20–30 dB of attenuation, while cross-talk, dispersion and timing issues become more severe with each newly introduced CMOS technology node. One way to alleviate this bottleneck is to radically change the interconnect technology. A promising approach is to drastically change the information carrier by the introduction of photonic interconnects. Indeed, optics as a wire replacing technology have some clear physical reasons for their superior interconnect characteristics as compared to their galvanic contenders [31] even at interconnect distances below a metre.

If we want to solve the interconnection bottleneck at the PCB and MCM level one of the great challenges for the next five to ten years is to adequately replace the PCB and intra-MCM level galvanic interconnects with high-performance, low-cost, compact and reliable micro-optical and micro-photonic alternatives. Such an optically enhanced interconnect approach should allow us to seamlessly extend the optical fibre data path to the very heart of the data-processing chips using e.g. polymeric wave-guides, free-space refractive, diffractive or hybrid plastic micro-optical components or a combination thereof.

However, these approaches can only prove their value in practical and economical viable real world systems if they can be made compatible with low-cost mass fabrication technologies and standard semiconductor packaging techniques. The creation of such micro-optical components, is one of the primary drivers for the continuous development of our in-house DPW technology. In the following sections, we will give a survey of the important components for photonic interconnects that were fabricated with the DPW technology so far.

3.1. 2D single mode fibre array couplers

High-precision 2D fibre alignment modules can offer great benefits for high-density photonic interconnects at the board-to-board and chip-to-chip level, where parallel light signals have
to be transferred between integrated dense 2D emitter and detector arrays. Even for the telecommunication infrastructure, the availability of highly accurate, low cost, field installable 2D fibre couplers would boost the further integration of fibre-optics in future fibre-to-the-home networks [32].

Although there are plenty of 1D connector components on the market, existing fabrication techniques like excimer laser photoablation [33], silicon micro-machining [34] and deep lithography with x-rays [35] have not shown to be able to create 2D connectors for single mode fibres that can be mass-fabricated with the required high accuracies and at low cost.

Using the DPW technology we were able to fabricate such a connector, which features conical shaped micro-holes to ease the insertion of single-mode fibres from the back-side of the fibre holder into sub-micron precision holes. The conical shape of the holes has been obtained by taking advantage of the ion–ion scattering effect of protons. This effect becomes pronounced when proton fluence is chosen in excess of $10^7$ particles $\mu m^{-2}$. The optimized micro-holes for fibre-insertion features a front-side diameter of 134 $\mu m$, and inner diameter to fit a fibre with cladding specification of 125 $\pm$ 0.7 $\mu m$ and a back-side diameter of 165 $\mu m$. A schematic view of the obtained micro-holes can be viewed in figure 8.

The connector plate features a $4 \times 8$ array of holes with a pitch of 250 $\mu m$. With the DPW technology we are capable of integrating alignment holes to the design via one single irradiation step. The fabricated alignment holes are three larger holes with a diameter of 700 $\mu m$, compatible with standard mechanically transferable (MT) ferrule pins. By measuring the rim of the micro-holes with an optical profilometer we find a standard deviation on the hole positions below 0.8 $\mu m$ (limited by the measurement apparatus). Although the conical holes allow for a tight control of the lateral position of the fibres, they still leave some angular freedom to the fibres. Therefore, we have opted to include in the DPW connector an additional mechanical pre-alignment plate, separated about 5 mm from the DPW plate, as illustrated in figure 9.

With this component, we measured an average in-line coupling loss of 0.06 dB in the telecom C and L bands. The maximum coupling loss over 37 link experiments was 0.15 dB[36]. The histogram of the connector losses over the whole array is shown in the right-hand side of figure 9.
3.2. Out-of-plane couplers for optical waveguides in standard FR4 PCBs

Today, a variety of technologies have been developed which allow the embedding of polymer-based optical waveguides into standard FR4 PCBs. This technique is very promising as it enables us to integrate relatively easily optical wires onto standard circuit printing technologies. However, one of the remaining challenges is to efficiently couple light in and out of the waveguides to various optoelectronic devices. In order to connect the optical signals to the surface mounted components a 90° turn is required which can be accomplished either electrically or optically. The electrical turn is conventionally introduced by an extra small flexible PCB board while the optical 90° turn is conventionally accomplished by a 45° micro-mirror.

Various techniques exist today to fabricate such angled facets on the embedded waveguides. Micro-machining techniques using 90° V-shaped diamond blades, reactive ion etching of the waveguides [37] and laser ablation [38] are among the techniques that are currently pursued.

Our concept differs from most approaches since we propose a pluggable out-of-planning coupling component [24] instead of writing the micro-mirrors directly in the waveguides. We believe such components can be easily mass-replicated from a master prototype. The replicated components can then readily be inserted in laser ablated cavities on the PCB to couple the light from the waveguide. The micro-mirror can either use total internal reflection or a metal-coated mirror to bend the light.

For the fabrication of this DPW component, we have chosen to use a proton beam collimating aperture of 125 µm, which causes some rounding in the corners of the component, as shown on the left side of figure 10, but this does not affect its optical functionality in any way. The design is such that once the component is plugged in, the micro-mirrors will reach 140 µm under the PCB surface. Non-sequential optical ray tracing predicts that when the component is plugged into a board with 50 µm × 50 µm waveguides and with a numerical aperture (NA) of 0.3, the coupling efficiency will be 73% (−1.37 dB). By using a metal coating over the micro-mirror, this efficiency can be further increased to 92% (−0.36 dB).

When testing the component directly (without the PCB waveguides) with multi-mode fibres at the entrance and the exit facet, we measure a maximal experimental coupling efficiency of 47.5% (−3.25 dB). This is in good agreement with a simulated efficiency for this configuration of 63.4% (−1.98 dB) considering the fact that we did not take scattering losses due to surface

![Figure 9](image-url)
Figure 10. Example of an out-of-plane coupler fabricated with the DPW. The component can be readily inserted in laser ablated holes for out-of-plane coupling from embedded optical waveguides in FR4 PCB. (a) Side view of the out-of-plane coupler, and (b) a view of the micro-mirror.

Figure 11. The free-space intra-MCM interconnection module mounted on top of a dense optoelectronic chips.

roughness into account for the simulations. The measured coupling efficiency increases to 56.5% (−2.49 dB) if we apply index matching gel between the exit facet of the source MMF and the entrance facet of the out-of-plane coupler.

3.3. Intra-MCM interconnect module

Whereas this simple out-of-plane-coupler can be fabricated with only a single irradiation and etching step, other more complex interconnection components require a more intricate combination of high-quality optical surfaces, spherical micro-lenses and micro-mechanical alignment features. An example of such a component is a prism-based intra-MCM interconnect module as shown in figure 11.

Density arguments can require free-space micro-optical interconnections even at the intra-MCM interconnect level. Our approach here is based on a micro-prism reflector which transports and routes data-carrying light beams from a micro-emitter to a micro-detector array, hence bridging intra-chip interconnection throws ranging between a few tens of millimetres to only a few millimetres. On its way from source to detector, each of the multiple beams are collimated,
bent at the 45° angled facets and refocused by micro-lenses. We have shown that this type of interconnect modules has the potential to provide the highly desirable massive parallel high-speed interconnects needed for future generations intra-MCM level interconnections [28]. We are currently working towards a massively parallel intra-chip interconnect demonstrator that will carry a channel density above 4000 channels cm\(^{-2}\) and hence provide us with low-cost, chip compatible, plug-and-play, commercially viable interconnect solutions [39]. In this study, we are not only looking at the fabrication of the module, but are also investigating how the component can be reliably attached above a dense optoelectronic chip [40]. We have therefore developed a solution consisting of a spacer plate surrounding accurately the optoelectronic chip. The spacer plate and the optical interconnection module are attached to each other via precise micro-spheres. The details of the design and a Monte Carlo analysis on the feasibility of the component can be found in [40].

4. Conclusions

We can conclude that the DPW is a viable technology for constructing prototypes of deep micro-optical structures with high aspect ratio. The basic process of DPW consists of irradiation of selected areas with swift protons. Two chemical steps can then be combined to either develop the high proton fluence areas by a selective developer or to swell circular footprint of the lower fluence into hemispherical microlenses. Through a series of optimizations for the irradiation set-up, the etching and swelling procedure, we are capable of making high-grade prototype micro-optical elements. This was illustrated by showing a selection of DPW components that can be used to overcome the limitation of galvanic interconnects at the board level.

A first component consists of a 2D single mode fibre array connector, with coupling losses below 0.15 dB. A second component is a pluggable element that can be used in combination with embedded optical waveguides within PCBs to couple light in and out of the waveguide. A third component features a free-space intra-MCM interconnection. The details of the package and its effect on the tolerance are described in [40].

Although a typical cycle time of about one day does not allow for mass production, we have shown that the DPW technology can be used as a rapid prototyping technology, capable of fabricating master components. These can be electroplated to form moulds for mass replication techniques such as hot embossing and injection moulding.

Acknowledgments

This study is financed by the EC 6th FP Network of Excellence on Micro-Optics NEMO, the FWO, IWT-GBOU, VUB-GOA, the DWTC IAP Photon network and the OZR of the Vrije Universiteit Brussel. CD is supported by a post-doctoral fellowship from the FWO Vlaanderen.

References

[1] Sinzinger S and Jahns J 1999 Microoptics (New York: Wiley-VCH)
[2] Smith H I and Craighead H G 1990 Nanofabrication Phys. Today 43 24–30
[3] Chen Y and Pépin A 2001 Nanofabrication: conventional and nonconventional methods Electrophoresis 22 187–207

New Journal of Physics 8 (2006) 270 (http://www.njp.org/)
[4] Vieu C, Pepin A, Carcenac F, Chen Y, Mejias M, Lebib A, Manin-Ferlazzo L, Couraud L and Launois H 2000 Electron beam lithography: resolution limits and applications Appl. Surf. Sci. 164 111–7
[5] Melngailis J 1993 Focused ion-beam lithography Nucl. Instrum. Methods Phys. Res. 80 1271–80
[6] Zankovych S, Hoffmann T, Seekamp J, Bruch J-U and Sotomayor Torres C M 2001 Nanoimprint lithography: challenges and prospects Nanotechnology 12 91–5
[7] Mihailov S and Lazare S 1993 Fabrication of refractive microlens arrays by excimer laser ablation of amorphous teflon Appl. Opt. 32 6211–8
[8] Becker E W, Erfield W, Hagmann P, Maner A and Munchmeyer D 1986 Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process) Microelectron. Eng. 4 35–56
[9] Zhang X, Jiang X N and Sun C 1999 Micro-stereolithography of polymeric and ceramic microstructures. Sensors Actuators 77 149–56
[10] Love J C, Anderson J R and Whitesides G M 2001 Fabrication of three-dimensional microfluidic systems by soft lithography MRS Bull. 26 523–8
[11] Acharya B R, Ramachandran S, Krupenkine T, Huang C C and Rogers J A 2003 Tunable optical fiber devices based on broadband long period gratings and pumped microfluidics Appl. Phys. Lett. 83 4912–4
[12] Rogers J A 2001 Rubber stamping for plastic electronics and fiber optics MRS Bull. 530–4
[13] Heckele M and Schomburg W K 2004 Review on micro molding of thermoplastic polymers J. Micromech. Microeng. 14 R1–R14
[14] Bohr N 1913 Phil. Mag. 26 1–24
[15] Kumakhov M A and Komarov F F 1981 Energy Loss and Ion Ranges in Solids (London: Gordon and Breach)
[16] Bethe H A 1930 Ann. Phys. 5 325
[17] Bohr N 1948 Mat.-Fys. Medd. K. Dan. Vidensk. Selsk. 18 144
[18] Fano U 1963 Annu. Rev. Nucl. Sci. 13 1
[19] Ziegler J F 1980 Handbook of Stopping Cross Sections for Energetic Ions in All Elements vol 5 (Oxford: Pergamon)
[20] Lee E H 1999 Radiat. Phys. Chem. 55 293–305
[21] Volckaerts B 2004 Deep lithography with ions PhD thesis Vrije Universiteit Brussel
[22] Vynck P, Volckaerts B, Vervaeye M, Ottevaere H, Tuteleers P, Cosentino L, Finocchiaro P, Pappalardo A, Hermanne A and Thienpont H 2002 Beam monitoring enhances deep proton lithography: towards high-quality micro-optical components Proc. IEEE/LEOS Benelux Chapter pp 298–301
[23] Papanu J S, Soane D S, Bell A T and Hess D W 1989 Transport models for swelling and dissolution of thin polymer films J. Appl. Polym. Sci. 38 859–85
[24] Van Erps J, Bogaert L, Volckaerts B, Debaes C and Thienpont H 2006 Prototyping micro-optical components with integrated out-of-plane coupling structures using deep lithography with protons Proc. SPIE 6185 33–46
[25] Ottevaere H, Volckaerts B, Vervaeye M, Vynck P, Hermanne A and Thienpont H 2004 Plastic microlens arrays by deep lithography with protons: fabrication and characterization Japan. J. Appl. Phys., Special Issue on Micro-optics
[26] Ottevaere H, Volckaerts B, Vervaeye M, Vynck P and Thienpont H 2003 Plastic microlens arrays by deep lithography with protons: fabrication and characterization Proc. 9th Micro Optics Conf. (MOC’03) pp 110–13
[27] Volckaerts B, Ottevaere H, Vynck P, Debaes C, Tuteleers P, Hermanne A, Veretenincoff I and Thienpont H 2001 Deep lithography with protons: a generic fabrication technology for refractive micro-optical components and modules Asian J. Phys. 10 195–214
[28] Debaes C et al 2003 Low-cost micro-optical modules for mcm level optical interconnections IEEE J. Sel. Top. Quantum Electron., Special Issue on Optical Interconnects 9 518–30
[29] Ottevaere H, Cox R, Herzig H P, Miyashita T, Naessens K, Taghizadeh M, Völkel R, Woo H J and Thienpont H 2006 Comparing glass and plastic refractive microlenses fabricated with different technologies J. Opt. A: Pure Appl. Opt. 8 S407–29
[30] Gomez V, Ottevaere H, Volckaerts B and Thienpont H 2005 Real-time in situ sag characterization of microlenses fabricated with deep lithography with protons Proc. SPIE 5858

[31] Miller D A B 2000 Rationale and challenges for optical interconnects to electronic chips Proc. IEEE 88 728–49

[32] Kim J et al 2003 1100 × 1100 port mems-based optical crossconnect with 4-db maximum loss IEEE Photon. Technol. Lett. 15 1537–9

[33] Proudley G M, Stace C and White H 1994 Fabrication of two-dimensional fiber optic arrays for an optical crossbar switch Opt. Eng. 33 627–35

[34] Suematsu K et al 2003 Super low-loss, super high-density multi-fiber optical connectors Furukawa Rev. 23 53–8

[35] Dunkel K et al 1998 Injection-moulded fiber ribbon connectors for parallel optical links fabricated by the liga technique J. Micromech. Microeng. 8 301–6

[36] Van Erps J, Volckaerts B, van Amerongen H, Vynck P, Krajewski R, Debaes C, Watté J, Hermanne A and Thienpont H 2006 High-precision 2d single mode fiber connectors fabricated through deep proton writing Photon. Technol. Lett. 18 1164–6

[37] Liu Y, Lin L, Choi C, Bihari B and Chen R T 2001 Optoelectronic integration of polymer waveguide array and metal-semiconductor-metal photodetector through micromirror couplers IEEE Photon. Technol. Lett. 13 326–8

[38] Van Steenberge G, Geerinck P, Van Put S, Van Koetsem J, Ottevaere H, Morlion D, Thienpont H and Van Daele P 2004 Mt-compatible laser-ablated interconnections for optical printed circuit boards J. Lighwave Technol. 22 2083–90

[39] Vervaeke M, Desmet L, Hermanne A and Thienpont H 2003 Alignment features for micro-optical interconnect modules Proc. 2003 Symp. IEEE-LEOS Benelux Chapter (January) pp 293–6

[40] Vervaeke M, Debaes C, Volckaerts B and Thienpont H 2006 Optomechanical monte carlo tolerancing study of a packaged free-space intra-mcm optical interconnect system J. Sel. Top. Quantum Electron. 12 988–96