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New silicon-based fibre assemblies for applications in integrated optics and optical MEMS

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ABSTRACT Nearly closed rhombus-shaped channels in micromachined silicon with very high accuracy for fibre array assemblies are presented. The fabrication and the assembly of fibres are described. The achieved accuracy is comparable with conventional V-groove assemblies. Additionally, rhombus-shaped channels allow new applications such as monitor pigtails with integrated photodiodes or buried fibre supplies in optical MEMS.

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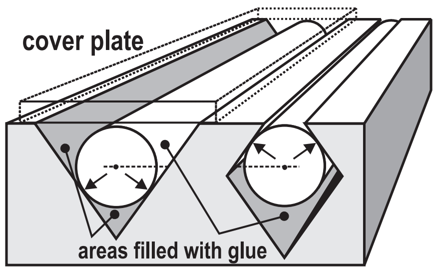

FIGURE 1 Fibre alignment structures: *left*, commonly used V-groove assembly with top plate for fibre protection; *right*, rhombus-shaped channel with fully protected fibre. *Arrows* indicate the lines of contact between fibre and alignment planes

1 Introduction

The increasing numbers of channels in WDM systems as well as the increased complexity of optical networks demand highly integrated optical devices such as waveguide gratings combined with rows of switches, channel monitors, or attenuators. Also the reduction in the on-board optical fibre interconnects becomes an important issue for optical systems as the number of channels increases. These advanced subsystems set a high standard for precise and highly reliable multifibre assemblies. Commonly, the fibres are assembled into precision-milled or etched U- or V-groove arrays [1, 2] before they are actively coupled to integrated optical devices. Additionally, the fragile bare fibres are protected against environmental influences by a cover plate (usually glass) that is placed on top of the fibres (Fig. 1, left).

Silicon micromachining allows fabrication of a new single-chip fibre assembly with rhombus-shaped channels below the wafer surface [3] (see Fig. 1, right). The overall assembly thickness can be as small as the integrated optical device. The achievable accuracy is proven to be comparable to common V-grooves, but the shape is unique to wet-etched channels in silicon. One of the main advantages compared to other types of assemblies is the reduced amount of resin for a reliable fibre gluing process. This results, in combination with the high elasticity of silicon, in reduced shear forces during temperature cycling.

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Moreover, the buried rhombic channels allow new applications. During device testing, temporary splices especially for fibre ribbons are required. Rhombic channels offer new possibilities for multifibre splices as they are easy to use and precise. A vacuum chuck replaces the glue in temporary splices.

A new approach is the use for combined fibre/monitor diode assemblies. This helps to reduce the number of on-board fibre interconnects because the monitor receivers can be integrated into a pigtail. In contrast to other monitor concepts (e.g. [4]), the integrated optical circuit itself remains unchanged.

2 Ribbon assemblies

2.1 *Design*

Figure 1 shows the new rhombus-shaped channel in silicon in comparison to well-known V-shaped alignment structures. Rhombus-shaped channels make use of the upside-down V-groove for the alignment. The position of the fibre core against the wafer surface is as precisely defined as in V-grooves, but, in contrast to V-grooves, a smaller channel opening at the wafer surface causes a deeper position of the fibre core. The overall size and shape of the rhombus is less important as long as the channel is large enough. The two lower planes of the rhombus are usually not well defined.

Figure 2 shows the width w of the slit vs. the core depth d below the surface for a rhombus-shaped channel and a standard fibre with a diameter of 125 μm. For a fibre that is precisely buried below the surface ($d = 62.5$ μm), a V-groove has

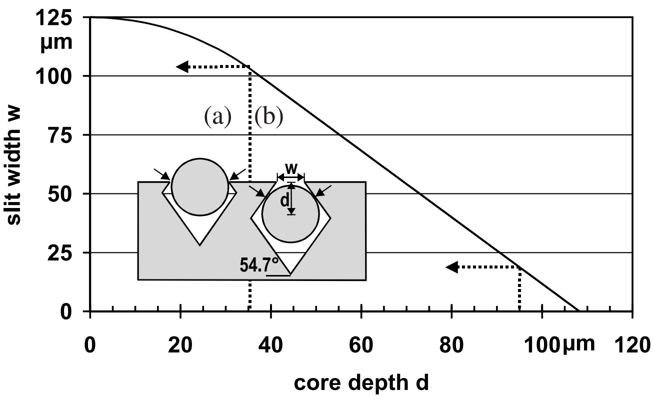

FIGURE 2 Width at the wafer surface vs. fibre core depth for a 125-µm optical standard fibre: (a) fibre hold at the edges only; (b) contact lines within the planes (preferred for a reliable alignment)

to have a width of 241 µm, while the slit of a rhombus-shaped channel is as small as 64 µm. Approximately 75% of the wafer surface (for a 250-µm fibre pitch) remains for the hybrid integration of further devices.

The core depth limits for these new channels are given by two boundaries. The first, region (a) in Fig. 2 with core depths between 0 µm and 35 µm is not suitable because the fibre is held at the edges of the triangular facets only and is therefore not very stable. The second boundary is defined by the achievable aspect ratio of the trench (see also Fig. 3). It strongly depends on the chosen technology for the trench (laser ablation, deep RIE etching, dicing or other mechanical techniques). Slit widths as small as 15–20 µm can be achieved, resulting in a core depth of about 90–95 µm.

The suitable range of the fibre core position is 35–95 µm. This range includes, in particular, a depth of 62.5 µm where the fibre is positioned just below the wafer surface.

Rhombus-shaped ferrules for multifibre assemblies allow an easy assembly of fibre-ribbon or multifibre assemblies. The wet etching process results in funnels at the end of each rhombus, which simplify the insertion of the fibres or fibre ribbons. Once inserted, the fibres cannot move into a neighbouring channel during device handling. The final gluing process encapsulates the fibre within the rhombic ferrule and guarantees the high accuracy of the fibre core position. The slit is broad enough to use UV-curing resins in most cases. The perfect alignment of the fibres against the two upper planes is achieved with very simple assembly tools and requires less effort than for V-groove assemblies.

Reliability problems are often observed with V-groove assemblies due to the large differences in the thermal expansion coefficients of glue on the one hand and silicon, silica and glass on the other hand. This causes shear forces during temperature cycling between the cover glass plate and the glue which often results in a fracture of the bond. The shape of the rhombic channels allows much smaller glue volumes. Furthermore, there are no shear forces between the glue and the surface. A certain degree of the force caused by the thermal expansion is compensated for within the elastic silicon that surrounds the fibre. Moreover, the surface/volume ratio is advantageous in rhombic channels: the small forces in the small glue volume are distributed over a large surface all around the fibre. For that reason, problems with delamination are reduced as compared to V-grooves, but this depends strongly on the type of glue, its thermal expansion coefficient and Young's modulus, and on the surface preparation. Different types of resins are currently under investigation.

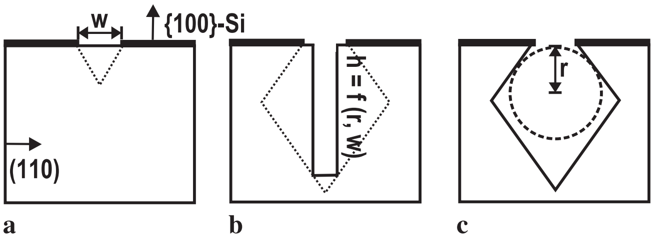

FIGURE 3 Fabrication of rhombus-shaped channels

2.2 *Fabrication*

The fabrication process is similar to the fabrication of standard V-grooves. At first, small rectangular mask openings are etched into a KOH-resistant mask layer on a standard [100]-silicon wafer using reactive ion etching (Fig. 3a). One additional step is required to convert a V-groove into a rhombus-shaped ferrule (see Fig. 3b): rectangular trenches are milled within the mask openings using a precision wafer saw. This step opens fast etching planes within the wafer. The required depth h depends on the slit width w and the fibre radius r. Precision milling as used here can also be replaced with deep silicon etching (RIE) or laser ablation. Additional trenches are milled perpendicular to the ferrules. During anisotropic etching, fast etching planes at the trench crossings result in funnel-like structures (Fig. 4a). Finally, the rhombus-shaped ferrules are formed in an anisotropic etching process in a standard KOH-etch. Four [111]-equivalent crystal planes around the trench define the rhombus. The sharp triangular facets along the wafer surface are well defined by the nitride mask. The two planes at the bottom of the rhombus are strongly affected by the shape and size of the milled trench and thus they are not suitable for alignment.

Inserting the fibres into the rhombi completes the fibre assembly. The ferrule-like structure (Fig. 4a) allows an easy assembly of multifibre pigtails. Fibres or fibre ribbons can be inserted easily. The triangular shape on the wafer surface operates as a guiding rail. Ribbons in which the uncoated fibre ends typically do not stay parallel after removal of the

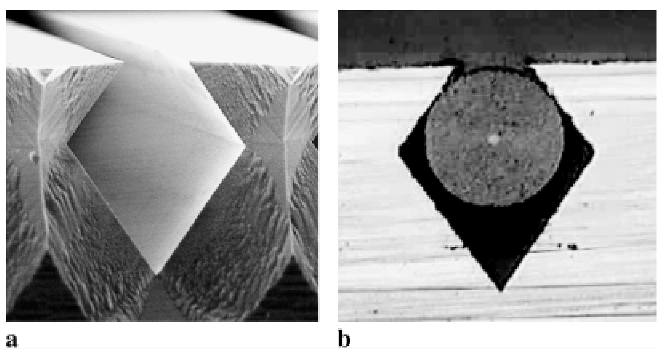

FIGURE 4 **a** Etched funnel at the end of a rhombic channel for simplified fibre insertion; **b** assembled fibre in a rhombic channel; the rhombus is completely filled with UV-cured resin

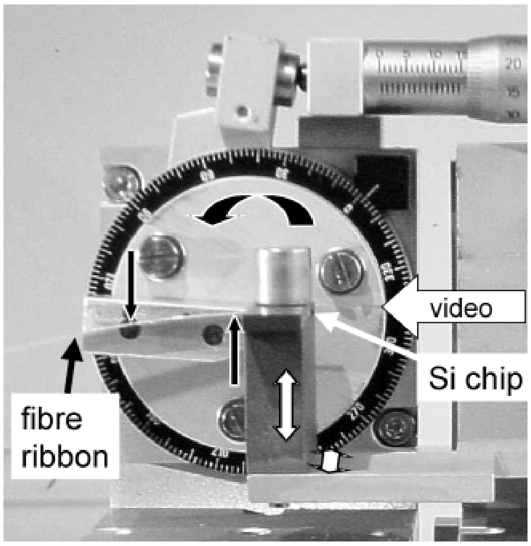

FIGURE 5 Tool for the fibre assembly in rhombus-shaped channels; fibres are adjusted by defined slight bending

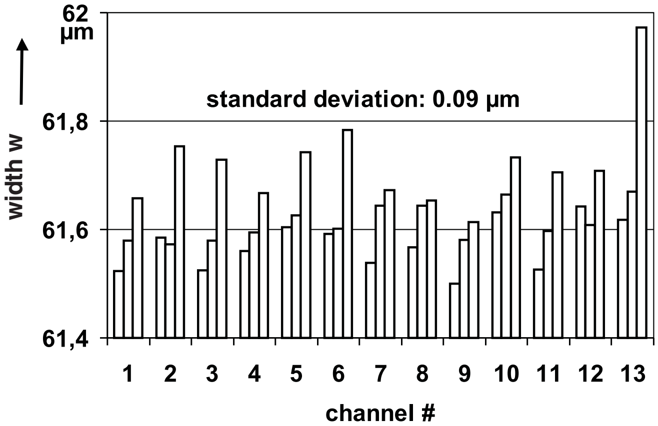

FIGURE 6 Measured width w in a 13-channel array at 3 different positions along the trench

primary coating can also be inserted due to the funnels. Finally, a good contact between fibre and alignment planes is achieved with a simple tool before gluing (Fig. 5): The fibres (or fibre ribbons) are bent in a well-defined way using a rotating platform; x-/y-stages allow a precise alignment along the channels. The precise alignment is controlled using a video system before the glue is dispensed at the fibre end until it can be seen at the video-controlled side. Any type of low-viscosity resin can be used to fill the channels completely due to the capillary force without soiling the surface. Here, UV-curing resins have successfully been used for a reliable fastening of the fibres.

The end face (Fig. 4b) is finally prepared with a wafer saw. Figure 4b shows an end face of a fibre assembly with mounted fibre. The rhombus below the fibre is completely filled with resin while no glue is found on the wafer surface. At this stage, the pigtail can be used for fibre coupling to integrated optical circuits. Polishing is not necessary as the roughness improves the surface adhesion.

3 Results: rhombus-shaped channels

Many 13-channel fibre assemblies were fabricated. The most important point for low insertion loss is an accurate fibre-core position within the array. The lithographic mask with its high accuracy mainly determines the pitch between two fibres while the core depth d relative to the wafer surface is given by the width of the trench. A fluctuation of the trench width of Δw directly influences the vertical misalignment of $\Delta d = \sqrt{2} \cdot \Delta w$; w and, thus, Δw were measured using a Leitz MPV-CD2 linewidth meter on more than 50 assemblies with 13 channels each. Figure 6 shows the result of a typical array, each 7.5-mm-long ferrule is measured at 3 positions. Typical standard deviations within the arrays are 0.08–0.16 µm.

Furthermore, the absolute position of the fibre core within assembled rhombus-shaped pigtails is measured using an integrated-optical 1×8-power splitter [3] as a reference. After optimising channel 1 and 8, each channel is realigned for maximum coupling efficiency and the necessary travel range is read out at the x/y-stages. The deviations are typically below 0.2 µm, the maximum deviation is as small as 0.6 µm. The resulting additional loss due to misalignments is typically below 0.2 dB (measurement limit).

4 Advanced applications

Rhombus-shaped channels offer a large number of new applications in optical components and optical testing.

4.1 *Temporary splices*

The simple insertion of optical fibre ribbons and the nearly closed rhombic shape allows their use in temporary splices. For this application, the chip with the channels is placed upside-down on a vacuum chuck (Fig. 7). The fibres are fixed within the alignment planes by the pressure difference. The closed shape guarantees a stable coupling during measurements and a good protection of the fragile bare fibre. The set-up shown in Fig. 7 simplifies the characterisation for multichannel devices in integrated optics and in fibre optics as it allows a simplified connection of pigtailed devices with fibre ribbons, but without connectors.

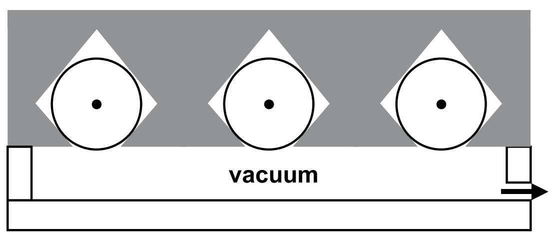

FIGURE 7 Temporary fibre splice based on rhombic channels on a vacuum chuck

4.2 *Fibre/monitor pigtails*

Furthermore, the deep core position of the fibres and the adjustable small slits on the wafer surface allow a hybrid integration of components above the channels. Especially, wavelength-division-multiplexed systems require, for example, power monitoring of all optical channels for an op-

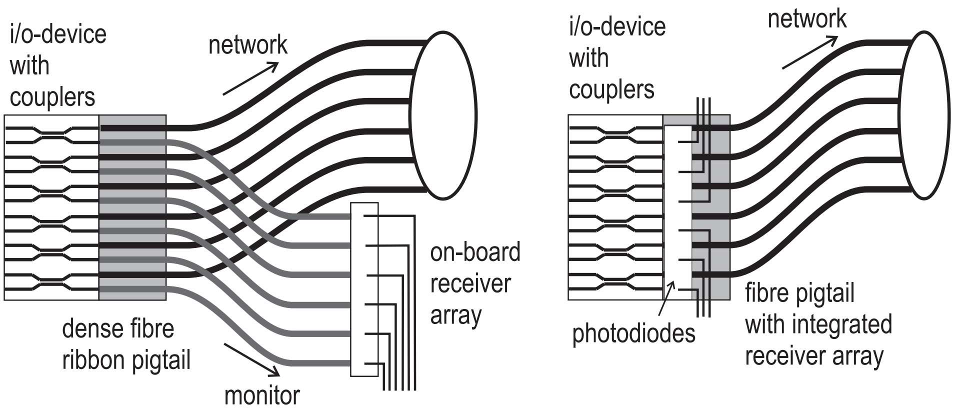

FIGURE 8 *Left*, common on-board power monitoring in optical subsystems; *right*, reduced number of on-board connections with integrated fibre/monitor pigtail

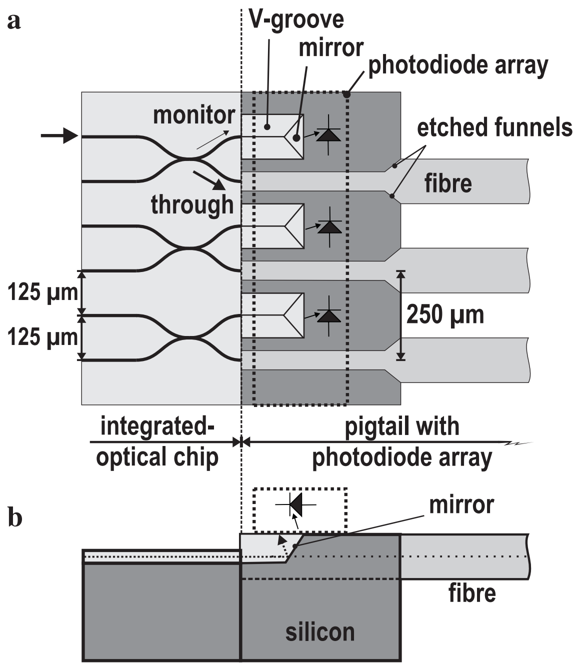

FIGURE 9 **a** Top view of a monitor pigtail coupled to an integrated optical device; **b** cross-section of the monitor channel with the mirror at the end of the V-groove

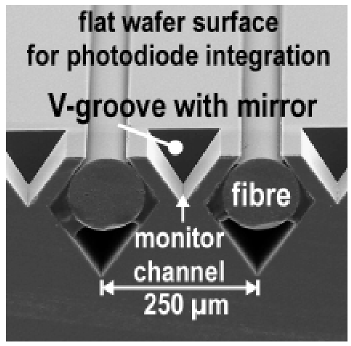

FIGURE 10 SEM photograph of a silicon chip as required for the monitor pigtail

timum system performance. So far, (integrated-)optical couplers separate a fraction of the transmitted light that is monitored in a separate array of photodiodes. This requires at least one additional on-board fibre ribbon connection (Fig. 8, left). Rhombus-shaped channels offer new opportunities for a higher degree of integration as the monitor diodes can be directly integrated into the fibre pigtail (Fig. 8, right). As the large number of fibres in optical subsystems becomes an important integration problem in multichannel systems such as DWDM-nodes, these new pigtails can simplify the assembly and improve the reliability of subsystems.

In this case, the fibre is completely buried below the wafer surface while, for example, photodiodes are placed on top of the wafer surface. With this technique, the number of necessary fibre connections on optical circuit boards can be reduced. It allows a direct coupling of the combined fibre/monitor pigtail to any type of integrated optical substrate (silica-on-silicon, glass, $LiNbO_3$, polymers or others). Moreover, the pigtail allows dense output channels with 125-µm or 127-µm (as currently used) fibre pitch. This pigtail is comparable to a dense fibre pigtail with two crossed fibre ribbons for the network (Fig. 8) and monitor channels. Due to the simple butt coupling it is suitable for any type of integrated optical substrate because no modification of the optical chip is required.

The principle of a combined fibre/monitor pigtail is shown in Fig. 9. Additional V-groove segments are inserted between the rhombus-shaped channels with fibres. The optical beam is reflected at the end face of the V-groove into a photodiode on top of the wafer. The mirror is achieved by a metal deposition in the V-groove. A similar design is commonly used for receivers (see, for example, [5]). Here, the buried fibres allow the integration of the monitor channels and the fibres into one single chip. This combined fibre/monitor assembly is unique to rhombus-shaped channels. Figure 10 shows the silicon chip with V-grooves/mirrors and mounted fibres, but without a photodiode array.

5 Summary

Fibre array assemblies with rhombus-shaped channels have successfully been fabricated. The single-chip silicon ferrules show an accuracy of better than $\pm 0.2\,\mu m$. The nearly closed ferrules with highly precise alignment planes and funnels at the end simplify the assembly of multifibre arrays.

These rhombus-shaped channels allow advanced devices due to the less structured surface of the silicon chip. An example is the monitor pigtail that allows the combination of the fibre assembly with a photodiode array to reduce the number of fibre connections in optical subsystems without modification of the integrated-optical device. In this case, a standard ribbon with a 250-μm fibre pitch can be combined with additional monitoring channels. This is an important step towards reducing the number of fibres required in monitored optical subsystems.

Further applications in integrated optical devices and optical MEMS seem possible because this technique allows us to bring the fibre closer to any point within an optical chip while the core position is precisely referenced to the wafer surface.

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