Design of In-Package MST-based Actuators for Micro-Assembly

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Abstract— **The paper describes the design of MST-based electrothermal actuation devices for lateral XY positioning of an optical fibre to a laser diode chip to improve their coupling efficiency and reduce the overall packaging cost. This is part of an investigation of the feasibility of an alternative method of performing micro-assembly tasks, i.e. by means of product-internal assembly functions.**

Keywords— **micro-assembly; fibre-chip coupling; micro-actuators; thermal actuation**

I. INTRODUCTION

This research aims at investigating the feasibility of the concept of micro-assembly using product-internal assembly functions, a novel concept in the micro-assembly domain. The functions include part actuation, position sensing and freezing of the part in its final position. Of these, the actuation and freezing functionality are subject to investigation in the research. Micro system technology (MST) is considered to be a key technology for the feasibility of the above-described concept, because of its possibility to create devices with small dimensions and high accuracy at potentially low cost (batch production). At least the actuation functionality is aimed to be performed using MST. Thermal expansion has been selected as the most promising actuation principle for the considered application.

The specific case under consideration is the coupling of an optical fibre to an optical waveguide on a chip. The actuation mechanism should position the fibre relative to the chip in all relevant degrees of freedom with sub-micrometer resolution. An iterative approach is taken, in which demonstrators are developed successively increasing in complexity. In the present paper the design and some modelling results of the first prototypes for lateral XY actuation are described. The first wafer process run is soon to be fabricated at the DIMES institute in Delft. Fixation functionality will be integrated in subsequent iteration steps.

II. MICRO-ASSEMBLY USING PRODUCT-INTERNAL ASSEMBLY FUNCTIONS

Performing micro-assembly tasks is technologically highly complicated due to the small part dimensions involved and the high accuracy demands in positioning. Overall part and product dimensions are in the range of about 0.5-30.0 mm and characteristic dimensions of (features of) parts can be in the range of 10.0-100.0 μm, while the demanded accuracy in relative position of features of parts varies between 0.1-10.0 μm. The assembly cost of micro-parts can constitute a considerable portion of the total product cost (sometimes up to 80%), due to the use of expensive machines and the involvement of delicate handwork. The micro-domain permits for the application of innovative methods of assembly. In [1] an overview has been presented of assembly methods as researched in the micro-mechanical engineering domain. The presented research focuses on the method of micro-assembly using *product-internal assembly functions*. Its feasibility is being investigated in the Laboratory for Precision Manufacturing and Assembly of the Delft University of Technology. In this method assembly functionality is created, which is integrated with the product to be assembled, and which remains as part of the product. The benefits that are aimed for are lower overall product costs and a higher product quality by reducing the amount of delicate micro-operations by human operators or expensive machines. The added functionality needs to be low cost, since it remains part of the product during operational life of the product. Besides lower overall costs and higher quality, also improved or additional product functionality can be achieved using this method.

The method is applied in a two-stage process. In the first stage coarse positioning of components is achieved using product external assembly functions, typically by a (semi-)automatic production machine or a human operator. The final, accurate positioning is done on basis of in-product assembly functions. Both coarse and fine positioning and fixation processes must be well adapted to each other to achieve an optimal overall result, in effectiveness as well as in efficiency.

The functions that apply for integration in the product are (1) controlled actuation of the component, (2) sensing the position of the component, and (3) freezing of the component in the final position, see Figure 1.

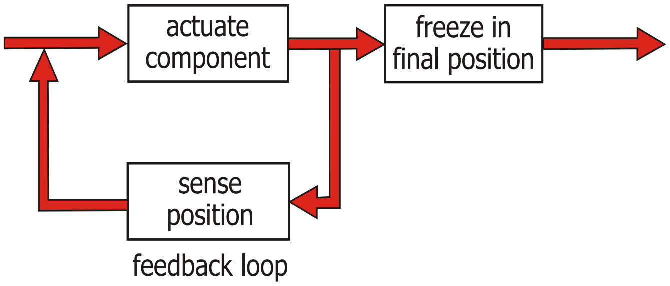


Figure 1. Product-internal assembly functions.

For freezing the component in the finally achieved position, two possibilities exist: either the component is definitively fixed after final alignment, or continuous control of the component position is applied during product life. Both options have distinct advantages and disadvantages, see [2], and are being considered in the investigation.

Micro system technology (MST) is considered to be a highly suitable technology for fabricating product-internal assembly functions, because of the small attainable feature sizes and very high accuracy. Due to the possibility of batch-wise processing it is potentially low-cost, which is essential since the functionality remains part of the product after alignment. For these reasons it is decided that at least the actuation functionality will be performed using MST.

III. CASE: OPTOELECTRONIC PACKAGING

The case considered for investigation of the method of assembly using product-internal assembly functions is the alignment of a single mode optical fibre to a laser diode, which is a challenging problem in optical telecommunication and sensing applications. This is embedded in the small dimensions of the laser output waveguide (typically 2 µm x 0.4 µm) and the optical fibre (8 µm core diameter; overall fibre diameter: 125 µm), see Figure 2 for a schematic laser diode layout. Alignment accuracy in the order of 0.1 µm in the lateral dimension has to be maintained to achieve sufficient coupling efficiency over the economic lifetime of the system. This accuracy cannot be achieved by hand in a reliable way. Very expensive machines are normally employed for the needed alignment and fixation steps, which last typically in the order of minutes.

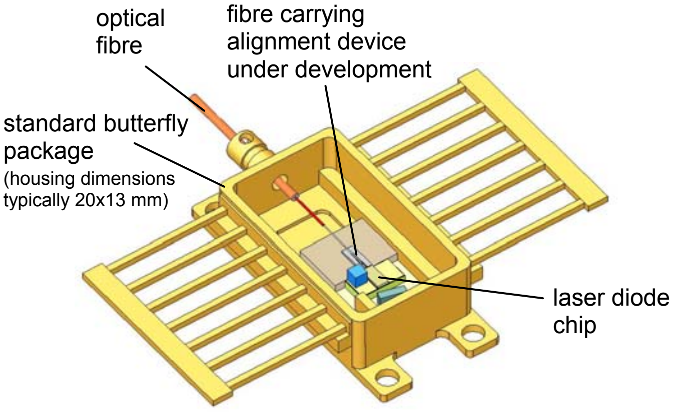


Figure 2. Schematic layout of a laser diode with optical fibre. Some parts have been omitted for simplicity.

A representative laser diode layout has been chosen that is commonly used in optical telecommunications. The primary target is to develop a reliable and reproducible interconnection technology for a single fibre to a laser diode using MST-based in-package actuators, by which the coupling efficiency and packaging yield are improved and the packaging cost is reduced. The focus is on *actuation* and *fixation*. Sensing functionality is not part of the investigation. The width of the subsystem should preferably be smaller than 250 µm, which is the standard pitch between two fibres, to make it suitable for use in multi-fibre applications.

Both the possibility of *permanent fixation* of the fibre with respect to the chip after final alignment and *continuous control of the fibre-chip position* during package life are being investigated. It is decided that at least the actuation functionality should be integrated with the product; the fixation solution is allowed to be applied externally. The end-goal is to have full control of all relevant degrees of freedom. Prototypes are being realised at the Delft Institute of Microelectronics and Submicrontechnology (DIMES). The remaining sections of the present paper are dedicated to presenting the progress made in the development of the first series of prototypes.

IV. DESIGN PROCESS

In this section the main issues related to the design process of the alignment devices are discussed. For clarity it is repeated here that an iterative approach is taken to benefit maximally from practical experience, which is acquired during the process. In a cyclic development path demonstrators are being developed increasing in complexity, intended to result in a system capable of realising a single-mode, single fibre-chip coupling, with full control of all relevant degrees of freedom. For the first prototype series it is decided that only the two degrees of freedom perpendicular to the fibre will have to be actuated. Moreover, the fixation functionality is not taken into consideration for the first prototypes. (In parallel, preparatory investigations are made to be able to integrate also fixation functionality into the system in following iteration sessions.)

The followed approach is that of a structured engineering design process. First the main boundary conditions and design requirements have been drawn up, together with a number of early design choices. Next, the most suitable actuation principle has been selected, followed by a structured concept generation process. Both thermal and mechanical modelling has been performed, and finally a manufacturing scheme for the first wafer layouts has been defined. The above steps will be reviewed, concluded by an overview of the present status of the research, the expected results, and the outlook for future investigations.

As mentioned in the previous section, the main *boundary conditions* for this research are that at least the actuation functionality should be product-internal, and that it should be achieved using MST-based manufacturing technology.

The product case at hand is a typical example of an *under defined design problem*, *i.e.* no clear, complete list of requirements can be drawn up. The reasons for this are twofold: on one hand it is not desired to focus on a specific product type only (instead, a more generic applicability is strived after), and secondly manufacturers are very reluctant in revealing sensitive information which could damage their competitive position. Therefore, only a limited design considerations overview is presented.

Main design considerations:

- Desired travel range at least 10-15 μm (based on possible coarse actuation accuracy);
- Forces in mN range (to overcome stiffness fibre);
- Minimum position resolution 0.1 μm;
- Small size (width preferably < 250 μm);
- Minimal complexity;
- Sufficient robustness;
- High general applicability.

Based on the above considerations, a set of initial design choices have been made:

Initial design choices:

- The actuation device will not be monolithically integrated with other parts of the laser diode system, it will be a separate part;
- Only one part will be actuated, which is decided to be the fibre tip;
- The base material will be monocrystalline silicon;
- The basic layout of the actuation device will be planar;
- Two possible basic layout orientations: with the fibre *in plane* or *through the plane* of the actuation device;
- Monolithic build up of the actuation device.

A monolithic build up of the actuator device is aimed for, because this has certain benefits: it combines less assembly steps with no play, no hysteresis, a simplified thermal design and relatively high stiffness. Of course this allows for small deformations only, which does not pose a problem in the considered situation. For a more in-depth treatment of the above mentioned initial design choices is referred to [2].

A. Actuator principle selection

The most important step in the conceptual design phase has been the selection of the actuation principle to be used for positioning of the fibre tip. For this, an extensive overview from literature has been compiled of all MST-based actuation principles that can be considered suitable for performing a significant mechanical load. It is decided to focus on ‘proven technology’ only for the actuation, both from functionality and from manufacturing point of view, since it is the purpose in the project to integrate existing technologies rather than to develop totally new technology for part of the functionality under consideration.

The forces needed to achieve 10-15 µm fibre tip displacement are calculated to be in the milli-Newton range. This travel range and force may appear very small, but in fact the number of MST-based actuation principles that can deliver this combination of displacement and force is highly limited. The most promising actuation principle for this application is thermal expansion, since it possesses by far the best capabilities to achieve the necessary workload. Also shape memory alloys (SMA) and piezoelectricity could in principle be used, but are only just capable of achieving the desired workload, and more complex in manufacturing and therefore more limiting in design freedom. They both suffer from hysteresis, making them rather complicated to control. Thermal actuation provides less difficulties: it generally consists of simple structures that can be made using proven technology with a limited number of manufacturing steps, and it has simple control due to quasi linear behaviour over a considerable temperature interval and due to the fact that it suffers little from hysteresis. However, it needs to be remarked that thermal loading might present unwanted complications, and therefore issues concerning thermal loading have been investigated further to obtain a better understanding to be able to take such issues into account.

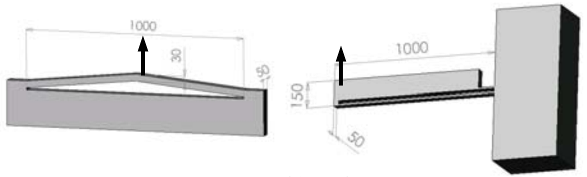
B. *Concept generation*

From literature three basic methods are identified for using thermal expansion as actuation principle actuation, see Table 1 below.

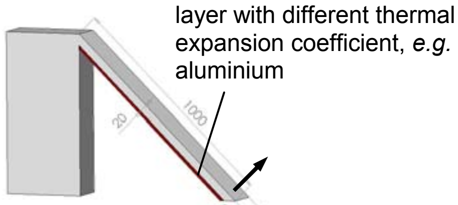
Method	Construction	Example
Linear expansion	One material	Simple straight beam V-beam structure
Difference in temperature	One material	U-beam structure
Difference in thermal expansion coefficient	More than one material	Bimorph beam

Table 1. Methods for using thermal expansion as actuation principle.

Schematic drawings of structures based on these principles are presented in Figure 3. The motion direction upon heating is denoted by arrows. In subfigure (a) Joule heating accounts for in-plane deformation of the V-beam, in (b) the difference in heating between the narrow and the wide arm results in in-plane bending of the structure, and finally in (c) a difference in thermal expansion coefficient results in out-of-plane bending of the beam. The typical dimensions displayed are sufficient for delivering the desired displacement and force values. For the presented examples no optimisation has been performed of the specific dimensions.



a) V-beam structure b) U-beam structure



c) Bimorph beam

Figure 3. Examples of thermal actuation structures (all dimensions in [µm]).

From such ‘building blocks’ as shown in Figure 3 four concepts have been constructed for actuation of the fibre tip in the directions perpendicular to the fibre. As previously mentioned two basic orientations of the actuation device relative to the fibre are investigated: *in plane* and *through the plane*. In Figures 4 and 5 respectively one in plane concept and one through plane concept are presented (again all dimensions are in [µm]). In Figure 4 the fibre is clamped between a V-beam structure and a passive spring. Horizontal motion of the fibre is performed by the V-beam and vertical motion by a bimorph beam with a metal layer on the bottom side. Figure 5 shows the fibre clamped between two U-beam structures and a passive spring. Upon heating the U-beams move sideways, thereby releasing the preload in the spring. The fibre can be inserted with both actuators in fully deflected state. Naturally, the overall device layout needs to be adapted to enable such a through plane configuration.

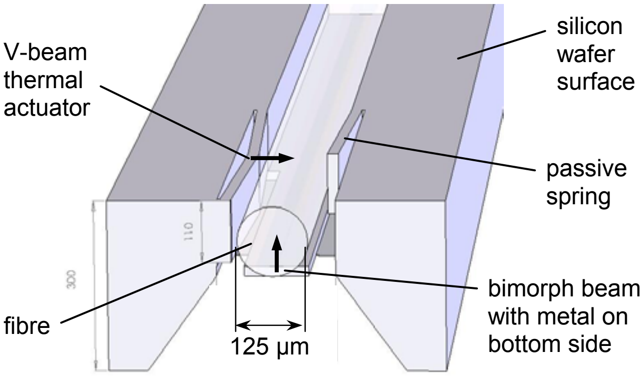


Figure 4. In-plane concept.

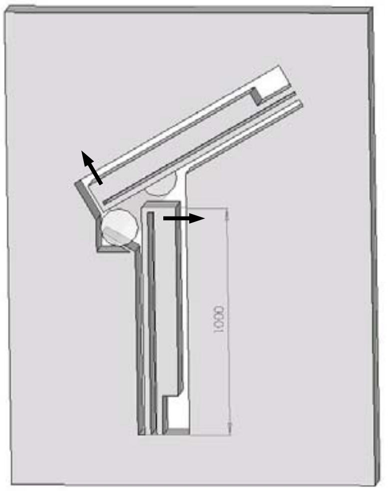


Figure 5. Through plane concept.

C. *Modelling results*

Mechanical and thermal modelling has been performed to predict the behaviour of the four individual concepts and to be able to optimise the geometries with respect to thermal loading and overall performance. Some of the modelling results that apply for U-beams are discussed here. For this analytical expressions and examples from literature (*e.g.* [3][4]) as well as (coupled field) finite element modelling has been used.

Using a U-beam structure of between 1200 and 1800 µm length it is possible to achieve free end-effector displacements of around 20 µm with a maximum temperature locally in the thin beam above 700°C. When the fibre is included in the model the displacement reduces to 10 µm, therefore the stiffness of the actuator in the motion direction is of the same order as the fibre. The heat necessary to achieve this result is approximately 0.5 W, with a typical heating time of maximum around 0.3 s. Fortunately, approximately 90% of the final deflection is already reached after 60 ms, which could be beneficial for control, especially when taking small steps. Cooling down of the device is also achieved typically in a few tenths of a second, so control can be relatively fast.

In contrast to intuition the local high temperature does not give problems. In silicon, which is an excellent heat conducting material, the heat can be transported away very fast. If heat sinking is taken care of adequately, the device is not heated up significantly. For example at only a few hundred micrometers away from the U-beam anchors the temperature has decreased to around ambient temperature, which is very beneficial for the device's overall position stability.

Heat transfer consists of *conduction*, *convection* and *radiation*. In principle conduction and convection can be modelled in most finite element packages. Conduction through air only plays a role when the air gap between the hot structure and its environment is small, for example smaller than 20 µm. Convection and radiation are both also highly dependent on the geometry of the direct environment and are therefore very difficult to predict with high accuracy. Conduction through solid material on the other hand can be modelled quite accurately. From examples in literature, *e.g.* [5] can be estimated that the combined effects of conduction through air, convection and radiation will not exceed 20% of the amount of heat transfer by conduction through the solid material.

For the considered concepts, not all relevant aspects were possible to be modelled; therefore experimentation is needed to enable a good assessment of the concepts. Another motive for performing experiments is to validate the used models for correctness of the results. Finally, fabrication of prototypes is desired to observe to what degree the fabricated real devices differ from their predicted state.

V. FABRICATION ISSUES

All four concepts can be fabricated using equipment available at the DIMES facility. Geometries have been chosen such that sufficient force and travel can be provided, and variants have been selected for optimisation purposes. All concepts can be repeated in a closely spaced interval, thereby enabling the possibility to be used for arrays of fibres, in which the fibre pitch is typically 250 µm wide.

Bulk micromachining is employed since this renders the possibility to fabricate sufficiently robust structures for the considered application. The actuation devices may not be damaged during the coarse assembly step, and they should be able to produce adequate force to overcome the bending stiffness of the fibre and provide sufficient fibre tip travel range. A considerable amount of out-of-plane stiffness is achieved through the use of a sufficiently large layer thickness, achieved by deep reactive ion etching (DRIE). This fabrication method can provide structures with smooth, straight sidewalls perpendicular to the wafer surface and a large design freedom in the wafer plane. Attainable aspect ratios are large, depending on the minimum desired feature size. With feature sizes down to 15 μm, the maximum device layer thickness is safely set to 120 μm. The backside is released using anisotropic wet etching. For all concepts process flows have been drawn up, including steps for implantation of doping materials and the placement of electronic connections. Some critical process steps have been determined, primarily associated with the fabrication of out-of plane bending bimorph actuators. Particularly the patterning of electrical leads, which needs to be performed on the backside in the anisotropically etched cavities, is a difficult process step that might provide complications. For this reason it is decided not to fabricate the complete prototypes in one wafer run, but instead to use two separate wafer runs to investigate different aspects, the first dedicated to achieving functional in plane U- and V-beam actuators, and the second one targeted at developing experience with fabrication of the out-of-plane bimorph actuators. Definitive mask layouts are being drawn and wafer processing will take place at the DIMES facility shortly.

A. *Experiment preparations*

Preparations for experimentations with the prototype structures have been performed. Test structures have been integrated into the mask designs to evaluate aspects that were difficult to model, such as grooves to investigate possible difficulties with the insertion of fibres, and to be able to assess the friction between fibre and device during actuation. Also locally structures have been placed that can serve as temperature sensors to verify the modelled temperature at that location with the real measured value.

VI. CONCLUSIONS AND OUTLOOK

An introduction has been presented on the method of assembly of micro products by building assembly functions inside the product, which is being investigated at the TU Delft. The case considered for investigation is the alignment of a single optical fibre to a laser diode. The main steps in the design process of the first prototypes as well as some modelling results have been reported on. For the first prototype series only the two degrees of freedom perpendicular to the fibre will be actuated, and fixation functionality is not yet taken into consideration. MST-based manufacturing technology is being employed for the product-internal actuation functionality. Thermal expansion has been selected as actuation principle for the specific application under consideration. Using MST-based technology very small and accurate assembly components can be manufactured. This can be produced at relatively low cost (batch wise fabrication), but still considerable design efforts have to be made in the design stage. It can be stated that the limited amount of available different MST-based manufacturing technologies are a restricting factor for the freedom of the designer, and hamper the possibilities for achieving an optimal functional design.

Wafer processing for the first prototype series will take place at the DIMES facility shortly, and experimental characterisation of the devices will take place in the following step.

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