Guidelines for Packaging of Microfluidics: Electrical Interconnections

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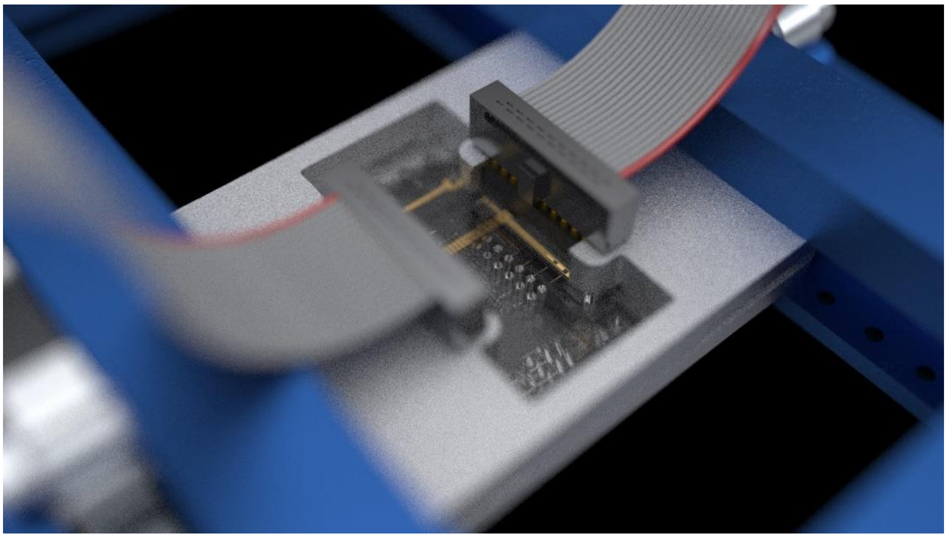

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1. Introduction

The last few years microfluidics stopped being a niche technology, with a user base predominantly consisting of engineers. Most of the microfluidic companies now are growing and the install base of instruments based on microfluidics is growing fast. Still, the situation is far from ideal. Designs are unnecessary complicated, there is little to no reuse of build-up expertise or developed components. Similar to the early computer industry, a major reason for the low popularity is the complicated character of microfluidic devices, specifically in terms of fabrication, and thus making them inaccessible to a larger population. [1]

In the ECSEL MFM project first steps have been made towards developing standards for microfluidic devices. Standards for basic design features like geometrical outlines and port locations have been proposed in white papers [2] and where adopted by ISO in an ISO IWA process. [3]

One of the complications of microfluidic products is the challenge of providing electrical connections. The average microfluidic engineer lacks electronic packaging knowledge. Furthermore, the incompatibility of microfluidics and electronics combined with space constrains, limits the technology choices.

Each of these technology domains has its own functions / requirements to fulfil:

Packaging in electronics [4]:

- electrical power distribution,
- electrical signal distribution,
- heat dissipation / thermal management,
- physical protection,
- manufacturability / automatic processing.

Electronic packaging is highly mature and is highly standardized by international standardization associations as IPC, ITRS and JEDEC. Fluidic packaging on the other hand, is in an early phase and is limited in standardization (see Figure 1.

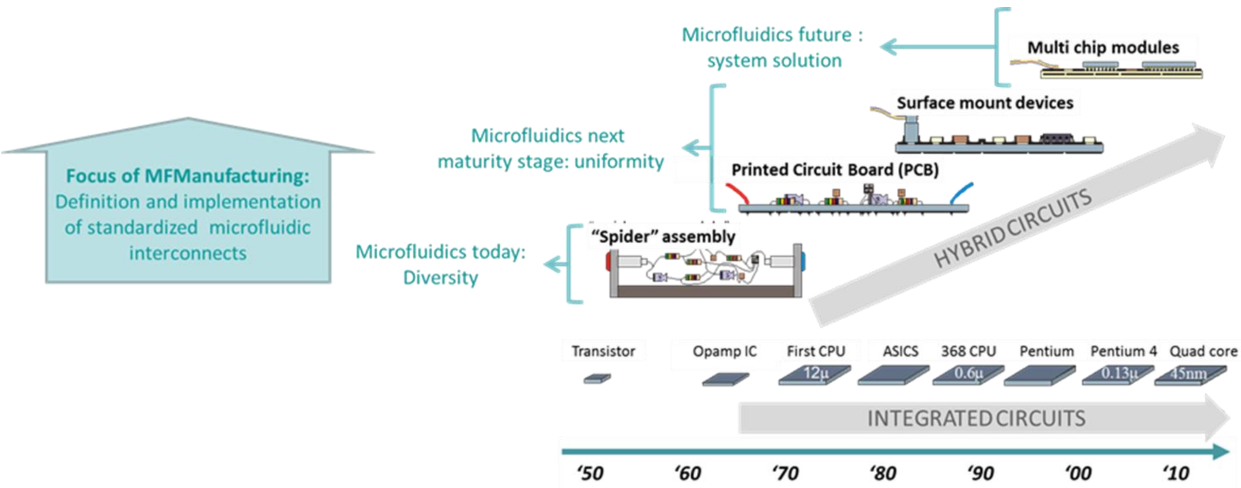

Figure 1: Maturity of Microfluidic Packaging compared to maturity in microelectronics (from MFM project proposal)

For microfluidic products, especially for hybrid systems where sensors or actuators are integrated in the product, packaging has to provide also for fluidic interconnections and in some cases also optical interconnections. Other requirements are:

- leak free microfluidic channels etc.,
- well defined microfluidic path (no dead volumes, sufficient lengths to ensure laminar flows etc.),
- no incompatible materials in the microfluidic path.

These additional requirements makes a microfluidic package much more complex than an electronic package.

2. Real world examples from the MFM project

Many commercial, high volume microfluidic products have been designed in such a way that some functions, such as electrical measurements, magnetic actuation, optical detection, valving, pumping, addition of chemicals are in the disposable. Of course implementation of these functions in a separate instrument makes the chip less complicated, less expensive, and better suited to be a disposable product, but that is often not possible and in such cases electrical connections between the instrument an de the disposable are needed for sensors, heating pad, pumps and valves etc. An example of such a device is micro gas chromatograph switch module of APIX (Figure 2). Valves and detectors need to be electrically connected to the fluidic circuit board to be able to switch gas flows and detect compounds in the gas flow.

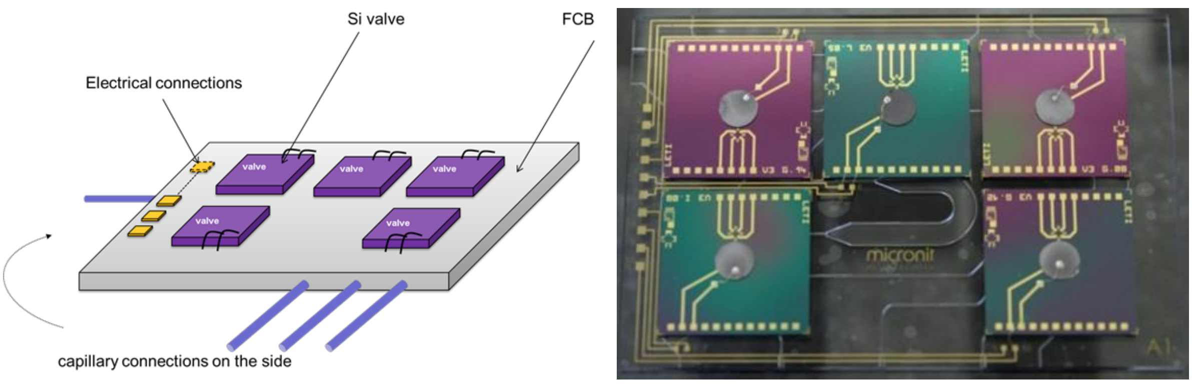

Figure 2: APIX micro gas chromatograph switch module, important functions on the fluidic device.

One can identify levels of interconnection in fluidic devices analogous to electrical devices [5]. In Table 1 a comparison of levels of interconnect between electrical devices and fluidic devices and examples of typical interconnection technology is given.

Table 1: Level of interconnection and typical fluidic and electrical interconnection technology.

Electrical Devices		Fluidic devices	
First level, e.g. chip	Solder, conductive adhesive, wire bond, (stud) bumps	First level microfluidic building block	Gasket, O-ring, dispensed elastomer
Second level, e.g. printed circuit board	Solder, connector, socket	Second level, e.g. fluidic circuit board	Ferrule, tube, connector
Third level, e.g. cabinet	Connector	Third level, e.g. instrument	Ferrule, tube, connector

3. Typical Microfluidics product: Lab on a Chip

The trend in microfluidics is towards higher integration and more complex systems [6]; especially in microfluidic products like organ-on-chip and implantable drug delivery systems. This leads inevitably to hybrid products and, in products were a small form factor is required, also to 3D integration. As said, often electrical interconnections between building blocks and between building blocks and fluidic circuit board are an essential part of the microfluidic system.
To be able to mass manufacture these complex systems in a cost-effective manner, the development of standard fluidic building blocks is essential. High volume production (typically above 1 million products per year) will tend to become monolithic devices for reasons of cost-effective production. Medium volume (around 100000 products per year) and low volume production (below 10000 products per year) are likely to be produced more cost-effective from standardized fluidic building blocks, with only limited use of expensive product specific components. Use of standardized building blocks is also especially relevant during development of new highly integrated microfluidic products for purpose of rapid prototyping and enabling short development cycles [7].

Specific for the microfluidic industry is that often electrical interconnection is needed not between two electrical conductors, as is electronic devices but between an electrical conductor and a liquid with biological or chemical content (e.g. potentiostatic measurements, heaters). A comment made by consulted experts was that the often used metals by microfluidic designers: Au, Pt and Pd are not allowed in a semiconductor frontend fab. Ti, TiN and TiW layers are proposed as alternatives.

4. Electrical Interconnections to Micro Fluidic devices

When electrical functions are not provided by an external instrument, electrical contacts are needed to power and control the on-board electrical functionalities. Typical functions on a chip that require electrical interconnections are:

- (Capillary) Electrophoresis.
- Heating.
- Flow measurements.
- Temperature measurements.
- Electrochemical measurements.
- Electrical impedance measurements.
- Mechanical actuation.
- Magnetic actuation.
- Electrical adjustment of surface tension.
- Lighting (for transmission measurement or microscopy purposes).

One can make a general distinction in functions (1) that require power and thus higher currents and (2) electrical functions that carry signals and in general have lower currents but can require shielding. Choice of a specific technical solution is highly depending on the specific requirements of the product function.

After discussion during the electrical interconnection workshop MF-Manufacturing General Assembly meeting in Grenoble (March 2017) the conclusion was drawn that at the current state of maturity and the large diversity in applications, guidelines for technology choices for electrical interconnections on a higher abstraction level are most useful.

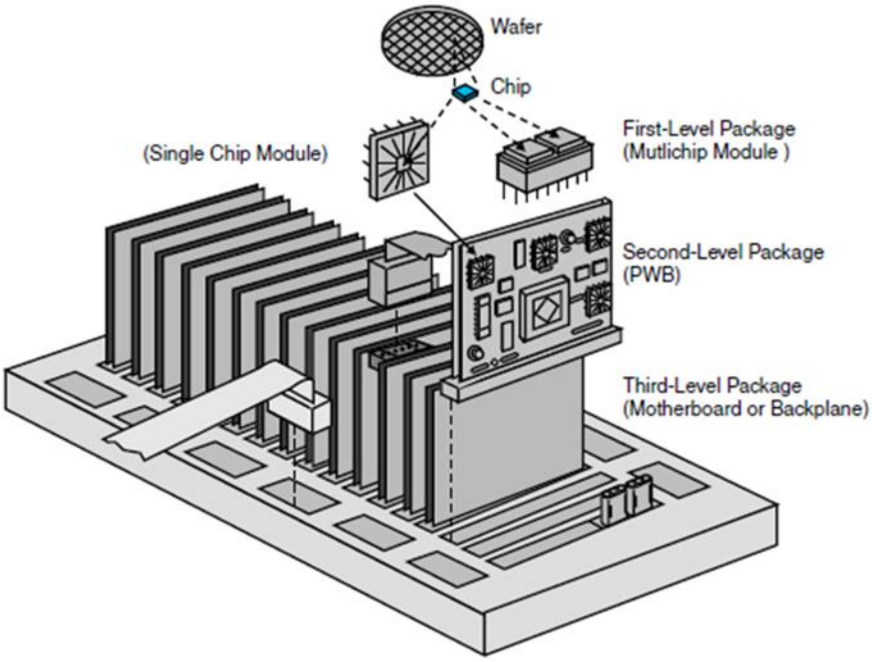

Figure 3: Packaging Levels used in Electronics (after [4])

Following the packaging levels [4] that are used in electronics, zero level (on chip), first level (between fluidic chip and fluidic board) and second level (between fluidic board and instrument) one can define similar typical electrical interconnection technologies. Electrical interconnections between a fluidic chip and a fluidic circuit board can be achieved by (1) wire bonding, (2) liquid solder or liquid metal and (3) conductive adhesive. Wire bonding is a very mature technology; Harman [8] estimates that between $8 * 10^{12}$ and $9 * 10^{12}$ wires are bonded per year. Most are used in the $160 * 10^{9}$ ICs produced, but many more are found in interconnect transistors, LEDs, etc.. Wire bonding requires that the bonding area is accessible by an ultrasonic transducer. An advantage of wire bonding is that wire bonding is a very mature solution for realizing electrical interconnections. A disadvantage of using wire bonding can lie in the accessibility of bond pads in 3 dimensionally designed products.

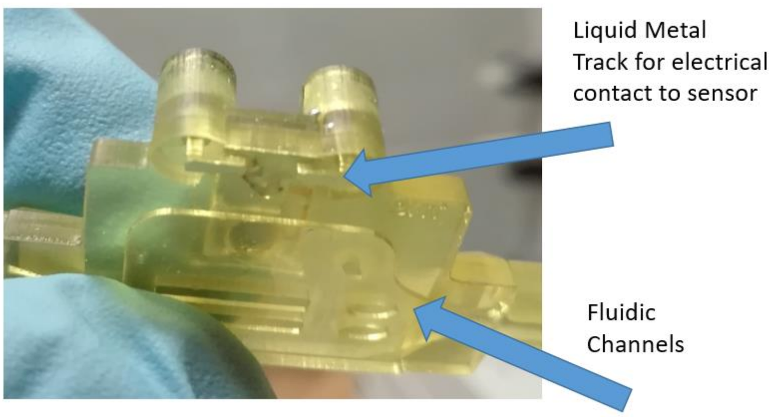

Figure 4: Example of a liquid metal interconnection to a sensor (3D printed particle detector made by TNO).

Injecting low melting point alloys, such as eutectic gallium indium (e-GaIn), into micro-channels at room temperature (or just above room temperature) offers a simple way to fabricate microelectrodes (see Figure 4). The channels that define the shape and position of the microelectrodes are fabricated simultaneously with other microfluidic channels (i.e., those used to

manipulate fluids) in a single step; consequently, all the components are inherently aligned. In contrast, conventional techniques require multiple fabrication steps and registration (i.e., alignment of the electrodes with the microfluidic channels), which are technically challenging. [9]
Liquid solder requires that the ratio between channel diameter and channel length allow a sufficient filling of the channels with conductive material. An advantage of liquid solder is that the interconnections are not permanent, thus allowing for repair or exchange of a fluidic building block. Good results with application of liquid metals in microfluidics, so-called microsolidics, have been reported [10], [11].

Traditional reflow soldering, as used in electronic manufacturing, with tin silver copper – leadfree-solders requires soldering temperatures above 250 °C. A main disadvantage of this type of soldering is that entire products have to be heated well above the melting temperature of the alloy. This can limit the use of specific substrate materials as well as leading to restriction in process flows. Alternatives for tin silver copper solders are tin bismuth solders that have a much lower melting temperature (Sn42Bi58 - 138 °C) or indium tin solders (In52Sn48 - 118 °C) Soldering can be used to create a hermetic sealing in combination with creating an electrical interconnect.

Use of conductive adhesives is a well-known solution in microfluidic devices [12]. As there is no generic conductive adhesive solution, finding a suitable solution for a specific application is not a trivial matter.

Flip chip connections can be made to ceramic and polymer substrates using either solder or adhesive interconnection systems. In microfluidics flip chip technology has been used in commercial products (e.g. Qmicro's gas chromatograph mentioned in [6]). Here a sensor chip is flipped over a fluidic channel, thus creating simultaneously an electrical and a fluidic interconnection [6]

In general, the fluidic circuit board has to be removable. This temporary aspect can be achieved by using well-known solutions from electronics, like (1) connectors, (2) clamping devices and (3) zebra foils [10]. In Figure 5 an example is given of a design of a clamp with retractable pins following MFM design rules. In Figure 6 a real clamp for electrical interconnection is shown.

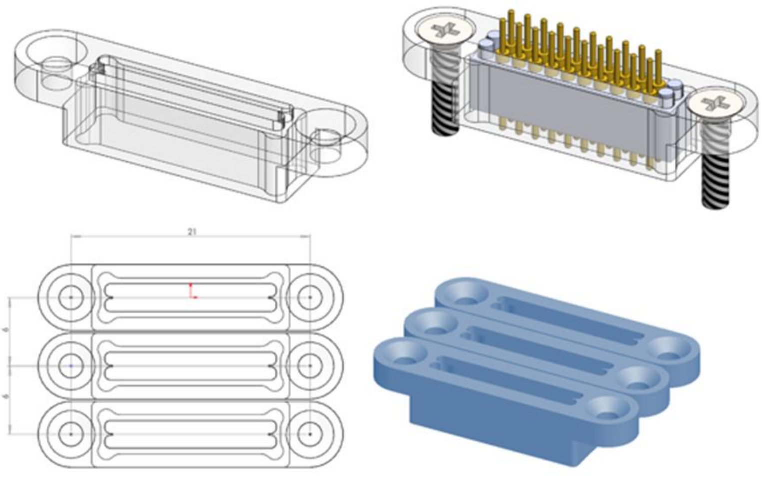

Figure 5: MFM clamp with a retractable pin-array for electrical interconnections.

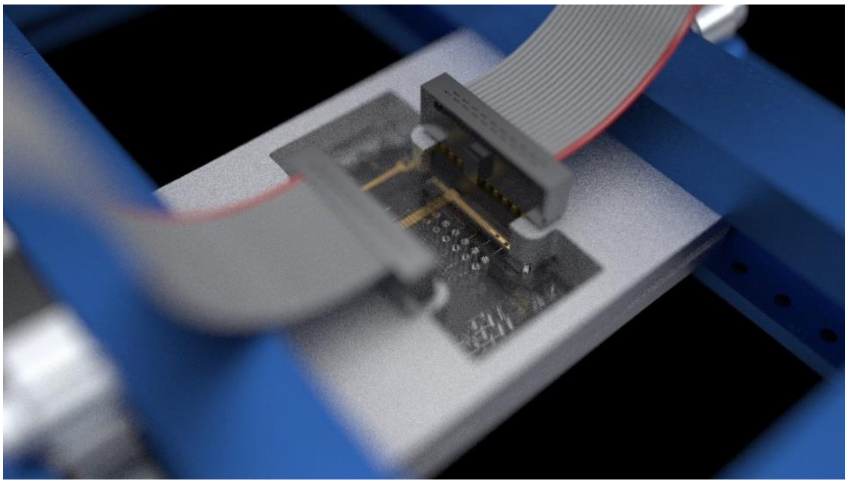
Figure 6: Example of a clamp with retractable pins (by Micronit)

5. Choice of Electrical Interconnection technology.

As shown above, there are many options to choose for electrical connections to microfluidic devices. Of course, the best option is not having electrical functions on the disposable, but when that is not possible, keep in mind the following considerations:

- Power consumption.
- Signal integrity: often the measured signals are weak and amplification in the disposable will give rise to additional cost.
- Cost.
- Manufacturability: not all discussed technologies have the same level of matureness.
- Process temperature: often the disposable contains biomaterial and even temperatures that the electronic industry regards as low, are too high for such materials.
- Is the connection mend to be permanent or temporary?
- Is the connection also used to create a hermetic seal?

Table 2: Evaluation of electrical interconnect technologies to be used in microfluidic disposables.

	Power	Signal	High frequency signal	Cost of solution	Manufacturabilility	Process Temperature	Permanent	Hermetic sealing	Temporary		Comment	MFM level 1	MFM level 2	MFM level 3
Soldering (PbSn eutectic)	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable			Not suitable		Interconnect process > 220 °C			
Soldering (SAC leadfree)	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable			Not suitable		Interconnect process > 250 °C			
Soldering (SnBi or SnIn)		Suitable	Suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Interconnect process > 150 °C			
Soldering (liquid metal eGaIn)		Suitable	Suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Interconnect process ~ 25 °C	Suitable		Not suitable
Flip Chip (soldered, adhesive, US)	Suitable	Suitable	Suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Flip Chip Can be used to close channels	Suitable		Not suitable
Use of Stud Bumps	Suitable	Suitable	Suitable	Not suitable	Not suitable	Suitable	Suitable	Not suitable	Not suitable		Stud bumps typical use is prototyping	Less suitable		Not suitable
Conductive Adhesive (ICA)	Suitable	Suitable	Less suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Dispensingneeds to be accurate	Suitable		Not suitable
Conductive Adhesive (ACA)	Suitable	Suitable	Less suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Potential smearing issues	Suitable		Not suitable
Conductive Adhesive (ACF)	Suitable	Suitable	Less suitable	Less suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Thermode bond process, access issues	Suitable		Not suitable
Copper Nano Inks	Less suitable	Less suitable				Less suitable	Less suitable	Not suitable	Not suitable		Limited experience in industry	Less suitable		Not suitable
Graphene Base Inks	Less suitable	Less suitable				Less suitable	Less suitable	Not suitable	Not suitable		Limited experience in industry	Less suitable		Not suitable
Integrated interconnects (e.g. use LTCC)	Suitable	Suitable	Suitable	Less suitable	Less suitable	Suitable	Suitable	Suitable	Suitable		LTCC is expensive technology	Suitable		Not suitable
Wire Bonding (Gold wire)	Not suitable	Suitable	Less suitable	Less suitable		Suitable	Suitable	Not suitable	Not suitable		Access to bond pads can be an issue	Suitable		Not suitable
Wire Bonding (Aluminium wire)	Suitable	Less suitable	Less suitable	Suitable		Suitable	Suitable	Not suitable	Not suitable		Access to bond pads can be an issue	Suitable		Not suitable
Wire Bonding (Copper wire)	Suitable	Suitable	Less suitable			Suitable	Suitable	Not suitable	Not suitable		Access to bond pads can be an issue	Suitable		Not suitable
TGV (Through Glass Via)	Suitable	Suitable	Less suitable	Suitable		Suitable	Suitable	Not suitable	Not suitable		Relative expensive in glass	Suitable		Not suitable
TSV (Through Silicon Via)	Suitable	Suitable	Less suitable	Suitable		Suitable	Suitable	Not suitable	Not suitable		Relative expensive in silicon	Suitable		Not suitable
Wireless data communication		Suitable	Less suitable	Suitable	Less suitable	Suitable	Suitable	Not suitable	Not suitable		Relative new approach for microfluidics	Suitable		Not suitable
Inductive power transfer	Suitable		Less suitable		Suitable	Suitable	Suitable	Not suitable	Not suitable		Relative new approach for microfluidics	Suitable		Not suitable
Flat connectors (e.g. ZIF)	Less suitable	Suitable	Suitable			Suitable	Suitable	Not suitable	Not suitable		Potential access issue	Not suitable	Suitable	Suitable
Zebra Foil		Suitable	Less suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable		Attractive when foil is also seal	Not suitable	Suitable	Suitable
Springs		Suitable	Less suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable		Good contact can be an issue	Not suitable	Suitable	Suitable
Retractable pins (including Pogo pins)		Suitable	Less suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable		Prefered temporatry interconnect	Not suitable	Suitable	Suitable
Connectors (plugs and jacks)		Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable		More difficult assembly than pins	Not suitable	Suitable	Suitable

Not suitable (red) | Suitable (green)

Less Suitable (yellow) | No opinion (white)

In Table 2 these considerations are evaluated[1], below a concise explanation:
Soldering is very well known and mature technology, however due to thermal restrictions related to the (polymeric- or bio-)materials used, soldering is less suitable. Use of liquid metal alloys is done in most cases for prototyping, there are a few companies that apply liquid metal alloys in their products. Flip chip, either soldered, glued or ultrasonic is an elegant method to seal a channel and simultaneously close an opening. It has been used in production of microgaschromatographs.

Stud bumping is a method to create bumps on a chip using ultrasonic bonding. In most cases the technique is used for prototyping purposes. For high volume bumps either can be applied using pick and place or electrochemical grown bumps.

As explained earlier, use of conductive adhesives requires careful selection of the specific adhesive material, adhesive bonding has the advantage that it is possible to make adhesive bonds at low temperatures – or when using UV curing adhesives – very fast curing. Potential disadvantages in the

[1] Some additions to this table were made after collecting feedback at the Microfluidic Standardization Workshop at imec (October 2017). The authors like to thank the experts attending this workshop and helping us clarifying the situation.

use are potential smearing and often limited pot life of adhesives, even stored at -40 degrees Celsius this can be a problem.

Copper nano inks and graphene inks appear to be promising, adaptation of these technologies in industry still is slow.

Integration of electrical interconnections can be done using ceramic cofiring materials (as LTCC and HTCC) An example if such technology is a flame ionization detector build by Fraunhofer. The cofired ceramic is needed as the sensor burns the material. So there is not only a need for withstanding high temperatures but also complete CTE matching
Earlier attempts have been made using PCB technology to embed channels in a printed circuit board (so-called MATAS technology) This integration in PCBs – although using existing technology- has never been successful.

Wire bonding is a mature technology, traditionally thin gold wire is used for signal and thick aluminum is used for power. Since ten years copper (palladium plated) wire bonding is replacing gold wire bonding.

Through Glass Via and Through Silicon Via are sometimes used as these technologies give additional design freedom and footprint reduction. These technologies are still relative new in microfluidics and apparently relative costly.

New in microfluidic is the use of wireless signal transport, omitting the need for electrical interconnects and also new is the use of inductive power transfer on a fluidic circuit board to a fluidic building block.

Connectors, springs and jacks are well known solution from microelectronics and have the advantage that the electrical connection can be detached.

6. Conclusions: Guidelines for Electrical Interconnections in Micro Fluidic products

As stated earlier given the current state of maturity and the large diversity in applications or technology choices, only some high level guidelines are given.

- The primary rule appears to be to avoid electrical interconnections in a fluidic device, if possible the functions that need electrical power and/or signals should be provided by an external instrument. The need for interconnections can also be avoided by integrating functions in a microfluidic building block.

- If one has to include electrical interconnections in a disposable, solutions with springs, clamps or connectors are preferred.

- It is recommended to group all electrical interconnects to a dedicated interconnection area. This can be done by partitioning the functions on the component and include electrical pathways on the fluidic board (or combine the fluidic board with a printed circuit board).

- It is recommended to perform reliability studies as done in electronic designs. During design e.g. design FMEA and process FMEA. During manufacturing field failure analysis, root cause analysis, etc. to better understand reasons for failing interconnection technology.

7. References

[1] K. Vittayarukskul, "A truly Lego®-like modular microfluidics platform," *Journal of Micromechanics and Microengineering,* vol. 27, no. 27, p. 035004+14, 2017.

[2] "ENIAC Project: MFManufacturing," [Online]. Available: www.mf-manufacturing.eu. [Accessed 13 06 2017].

[3] ISO, "IWA 23:2016 Interoperability of microfluidic devices -- Guidelines for pitch spacing dimensions and initial device classification," [Online]. Available: https://www.iso.org/standard/70603.html. [Accessed 13 6 2017].

[4] R. Tumala, Fundamentals of Micro Systems Packaging, ISBN-13: 978-0071371698 : McGraw-Hill, 2001.

[5] G. Perozziello, Packaging of microfabricates devices and systems, Ph.D. thesis: DTU, 2006.

[6] D. E. Angelescu, Highly Integrated Microfluidics Design, ISBN 9781596939790 : Artech House Publishers, 2011 .

[7] N. P. McDonald, Microsystems Manufacturing Technologies for Pharmaceutical Toxicity Testing, Glasgow: Ph.D thesis University of Glasgow, 2013.

[8] Harman, Wire Bonding in Micro Electronics, ISBN 9780071476232 : Mc Graw Hill, 2010.

[9] J.-H. So, "Inherently aligned microfluidic electrodes composed of liquid metal," *Lab on a Chip,* vol. 11, no. 5, pp. 905-911, 2011.

[10] A. C. Siegel, "Microsolidics: Fabrication of Three-Dimensional Metallic Microstructures in Poly(dimethylsiloxane)," *Advanced Materials,* vol. 19, pp. 727-733, 2007.

[11] T. W. Herling, "Integration and characterization of solid wall electrodes in microfluidic microfluidic devices fabricated in a single photolithography step," *Applied Physics Letters,* vol. 102, pp. 184102 - 184105, 2013.

[12] R. A. Brennen, "Integrated microfluidic and electronic components". Patent US 6632400 B1, 14 10 2003.

[13] C. Pepponet, *Integration dún protocole biologique complet dans des laboratories sur puce,* CEA LETI, 2009.

[14] M. Burns, "An Integrated Nanoliter DNA Analysis Device," *Science,* vol. 282, pp. 484 - 487, 1998.

[15] H. v. Heeren, "Standards for connecting microfluidic devices?," *Lab Chip,* vol. 12, p. 1022, 2012.

[16] Z. Zhang, "Design and fabrication of a polymer-based instrumentes microbioreactor for High-throughput continuous microbial cell cultures screening," *AlChe05.*

[17] W. Ko, "Packaging of microfabricated devices and systmens," *Material Chemistry and Physics,* vol. 42, pp. 169 - 175, 1995.

[18] D. Issadore, Point-of-Care Diagnostics on a Chip, ISBN 978-3-642-29267-5: Springer, 2013.

[19] H. v. Heeren, "Design Guideline for Microfluidic Device and Components Interfaces," EU MFM Project, 19 4 2016. [Online]. Available: http://mf-manufacturing.eu/wp-content/uploads/Design-for-Microfluidic-Interfacing-White-Paper-version-1.0.pdf. [Accessed 6 6 2017].

[20] "IWA 23:2016 Interoperability of microfluidic devices -- Guidelines for pitch spacing dimensions and initial device classification," ISO, [Online]. Available: https://www.iso.org/standard/70603.html . [Accessed 13 6 2017].