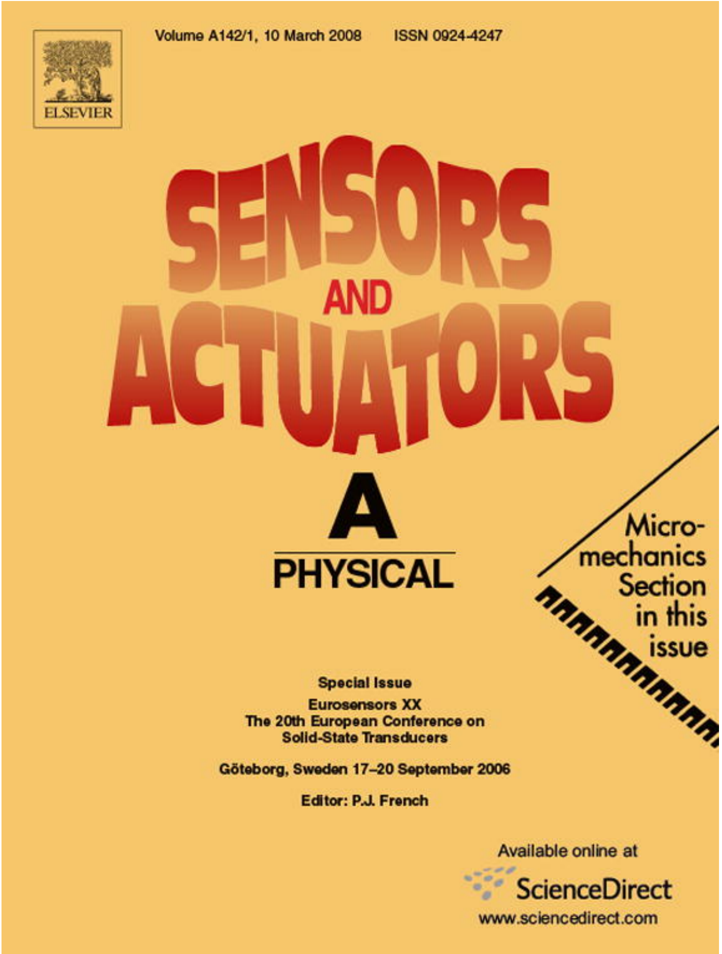
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Flip chip microassembly of a silicon triaxial force sensor on flexible substrates

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Abstract

Miniaturization of microelectromechanical systems (MEMS) based devices can be achieved by flip chip assembly directly onto a flexible circuit substrate. The main goal of this work was the selection of a suitable bonding material and process to enable scaling down of MEMS sensorized devices for biomedical applications. Finally, the heat bondable anisotropic conductive film 5552R (3M) allowed mechanical robust and low resistance electrical bondings together with a short process cycle time.

Keywords: MEMS; Microassembly; Anisotropic film; Bonding; Flip chip

1. Introduction

Microelectromechanical systems (MEMS) derive from the integrated circuit (IC) processes. This technology enables the fabrication of sensors and actuators in the micro-scale. To enable mechanical and electrical system integration of these fragile devices, they are usually mounted on a support structure and connected by wire bonding [1,2]. This approach has the drawback of a substantial increase of the overall dimensions. The electrical connections achieved by wire bonding usually give low reliability and increase space requirements. Reduction or elimination of this support structure leads to a substantial further miniaturization of the overall device. This work describes flip chip bonding of a silicon MEMS sensor directly onto a dedicated flexible substrate, avoiding the need for an additional support, thus reducing the overall dimensions and total assembly time as no wire bonding is needed. Moreover, an increased mechanical robustness was achieved.

A hybrid silicon triaxial force sensor has been fabricated [2] and characterized [3] by the authors. It consists of a sensing chip (Fig. 1A) that comprises four tethers whose axes are perpendicular to each other, and a column, located at the centre, which transmits the force. Four piezoresistors, positioned in high strain areas of the bottom side, are used independently in order to measure the three components of an applied force through a fractional change in resistance. The sensor dimensions are 1.5 mm × 1.5 mm × 0.65 mm. The four p-type piezoresistors are connected to eight Ni/Au bumps (Fig. 1B) with a diameter of 200 μm. As reported in Ref. [2], a first solution for the sensor assembly was to bond it to a silicon support having dimensions of 2.3 mm × 2.3 mm × 0.7 mm. The wafers for the carrier chips were processed to include Au pads with a layout corresponding to the one of the pads on the back side of the sensing chip (Fig. 1B). The technological process for the carrier chip was a two mask process with which gold pads and connections were realized via a lift-off process. Different design cases for the metallization layout of the support chip were developed in order to allow flexibility of packaging. This has been done in order to implement different types of possible working configurations of the sensors. In fact, the layout of the pads somewhat dictates the layout of the external connections of the single sensor. However, this solution is strongly limiting since if a new layout is required, a full silicon process must be performed.

A conductive polymeric glue (H37MP, Epotek Technology, Billerica, MA, USA) was used to perform the bond between the corresponding pads of the two chips. Therefore, a robotic station

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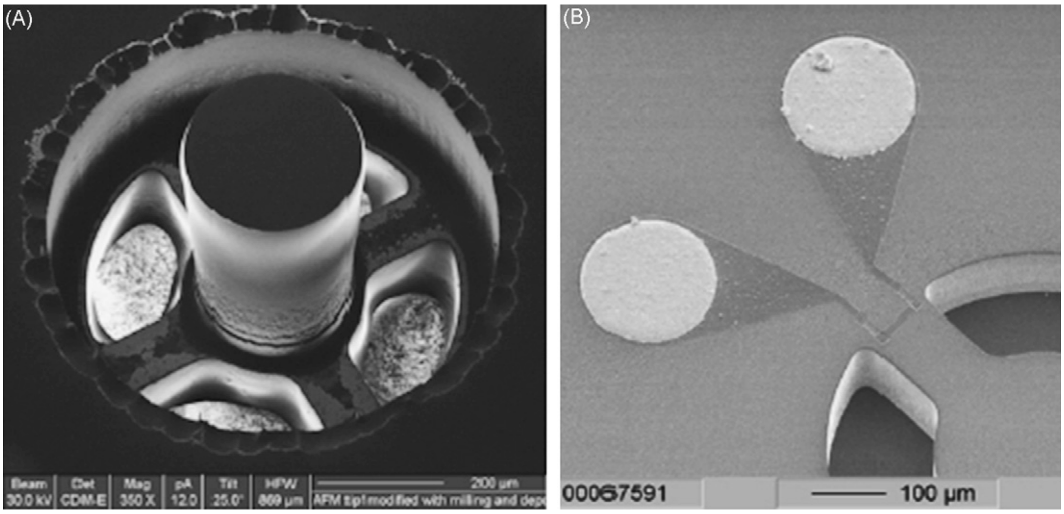

Fig. 1. (A) FIB image of the sensor, (B) piezoresistors and pads.

for glue dispensing and sensor chip manipulation was used. The result is represented in Fig. 2.

The spacing between the sensing element and the silicon substrate, that was about 30–40 μm in thickness, was constrained by the polymer bond. It must be constant for the sensor to properly detect the three components of applied forces. Although the glue was dispensed in fixed amounts with an automatic, reliable system, curing of the glue caused the sensing chip to be not perfectly parallel to the support chip.

This kind of sensor assembly was used in a novel cylindrical shaped minimally invasive surgical tool [4] and tactile flexible skin applications [2] as reported by the authors. Especially in Ref. [4], where miniaturization is highly desirable, the major dimensions were determined by the point that the silicon support (with its dimensions of 2.3 mm × 2.3 mm × 0.7 mm), where the force sensor is glued on, must be wire bonded to outer circuitry to achieve electrical connections. This needs additional space around the support (4 mm × 4 mm area is required, including support plus wire bonding), thus resulting in a device outer diameter of 7 mm, instead of just the 2.3 mm required if the bare force sensor was used. In that case the force sensor requires an area of 1.5 mm × 1.5 mm, then, considering the outer device walls, it results in an approximate device outer diameter of 2.3 mm. Moreover, the electrical connections achieved with wire bonding are not robust enough to be used in a surgical scenario, since they move and then they may introduce high noise level to the sensor recordings.

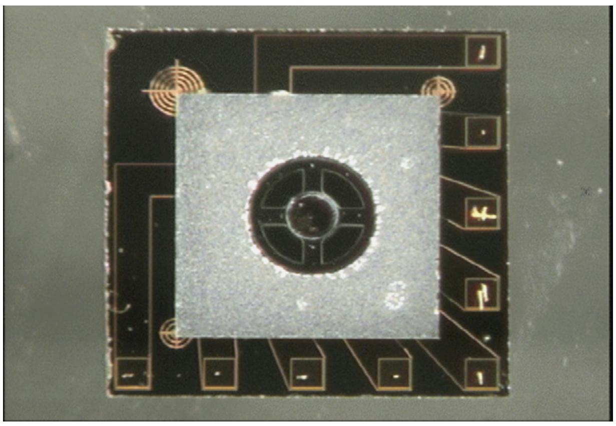

Fig. 2. Final sensor chip obtained by using the previous process.

Starting from these needs, further miniaturization could be enabled by mounting the sensor directly on a flexible electrical circuit, so that this support is no longer needed. A flexible circuit has been obtained from LF9150R Pyralux (DuPont, USA). High-resolution copper tracks have been shaped by using MicroPosit S1813 photoresist (Shipley, USA) in a photolithographic process. The contacts of the piezoresistors must be electrically bonded to 250 μm circular contact pads on the flexible circuit. Furthermore, reliable and strong mechanical bonding is required.

To achieve these connections three different flip chip bonding techniques were tested—bonding with conductive glues, solderpaste and anisotropic conductive film.

2. Microassembly station

A microassembly station was designed and built up to enable bonding of the sensor for flexible circuits by using glues, soldering paste and anisotropic conductive film and to allow maximum flexibility in the assembly process, where all the relevant parameters can be changed easily and quickly. The core components of this set up (Fig. 3) are a aluminium microhotplate mounted on a *xy* stage and a suction gripper with an integrated load cell (0.20 N) sensor carried by a Nanoslider (1DOF in *Z*-axis) [M111.1DG, Physik Instrumente (PI) GmbH & Co. KG, Germany]. A soldering iron [WSD 81, Weller, Germany] is the heating element in the hotplate (Fig. 4). The actual temperature of the hotplate can be measured and displayed with a precision thermocouple monitor [Stanford Research Systems, SR 630]. Additionally, an integrated peltier element allows active cooling.

Furthermore, a specially developed adapter allows connection of the flexible circuit and measurement of the resistances between the tracks. These resistances should drop from >10 MΩ

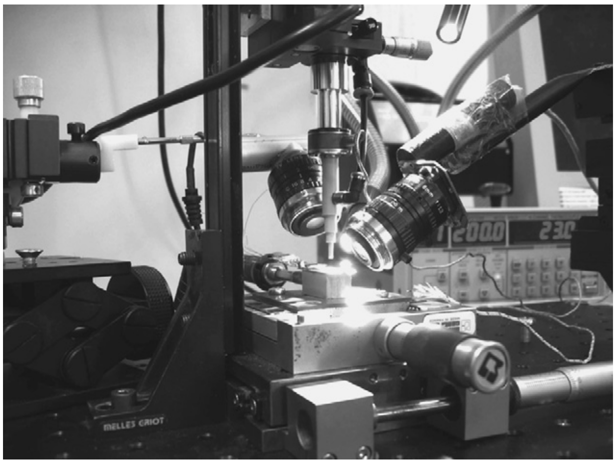

Fig. 3. Microassembly station.

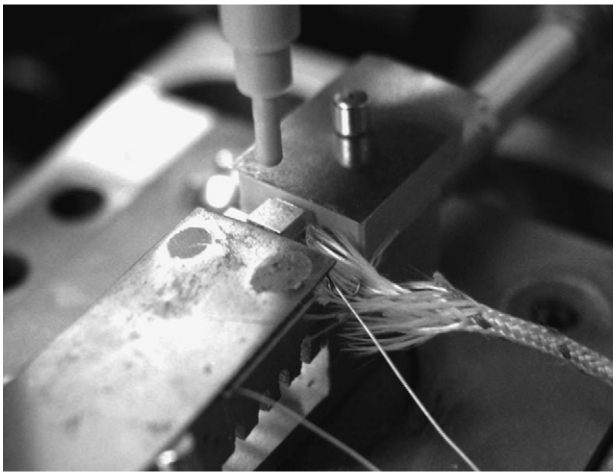

Fig. 4. Microhotplate.

to the 700 Ω–1 kΩ of a piezoresistor in the case of a properly mounted sensor.

The signals from the load cell and the temperature measurement unit are captured with a data aquisition card (DAQ6062E, National Instruments) under National Instruments Labview 7.0.

Together with the Nanoslider controlled via serial port and the load cell as force sensing element, a closed loop control allows the application of a uniform load during the curing process. Moreover, a load profile dependent on the temperature of the load cell is realizable with this configuration.

The closed loop control is also necessary as the force on the resistor is applied by pressing on the sensor down on the flexible circuit with the Nanoslider. Heating up the hotplate also results in thermal expansion, so the forces on the sensor would increase without the correct readjustment within the closed loop control.

For conductive glue dispensing a syringe with a 30 gauge needle (300 μm outer diameter) driven by a microdispenser [EFD, 1000XLE] is mounted on a PC controllable 3DOF micromanipulator [DC3-R-L, Marzhauser-Wetzlar, Germany]. At this point the dispensing system is already ready for a future complete automatisation.

Two USB microcameras with an optical field of approximately 2.5 mm × 2 mm allow a precise alignment of the sensor on the substrate and can also be used for automatisation purposes under National Instruments Labview together with a suitable image processing toolbox.

3. Conductive glues and soldering

At the beginning the flexible circuit is cleaned with Industrial Electronic Cleaner (CRC Industries Europe S.A., Zele, Belgium) and fixed on the microhotplate using magnets. The sensor is then picked up with the suction gripper and correctly aligned on the pads of the flexible circuit. Then the sensor is lifted 10 mm up and held in this position, retaining the *xy* position relatively to the flexible circuit.

In the next step solderpaste or conductive glues are dispensed onto these pads (Fig. 5A). For this task the micromanipulator is driven manually with the master unit. Future automatic dispensing is feasible using the PC interface for the micromanipulator.

Ablebond 84-1LMISR4 and 826-1DS [Ablestick Laboratories, England] are conductive die attach adhesives that can be dispensed through a 30 gauge needle. Solderpaste with a particle size of 5–15 μm [Felder GMBH Loettechnik, Oberhausen, Germany] can also be processed with the same set up. After placing the sensor again (Fig. 5B) on the hotplate the glue is cured at 150/175 °C for 30/60 min. Solderpaste needs heating up to 220 °C for about 10 s.

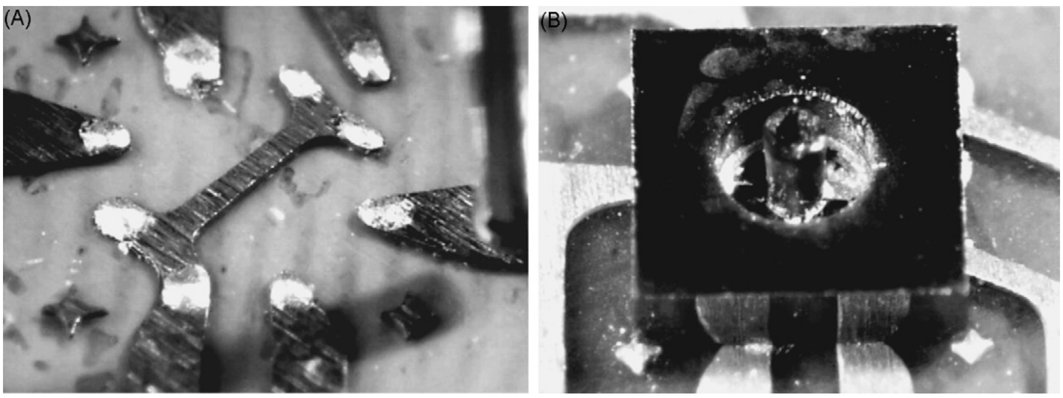

Fig. 5. (A) Dispensing, (B) placed sensor.

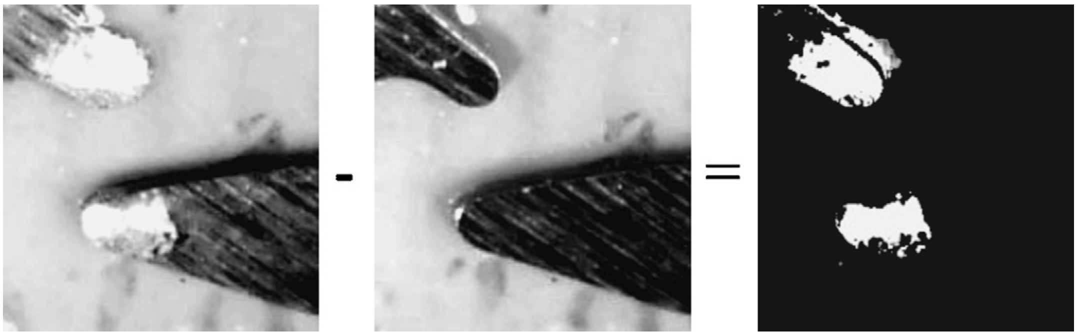

Fig. 6. Image processing steps.

A problem in dispensing conductive glues or solderpastes that may occur is partial clogging of the dispensing needle. Determining the size of the dispensed droplets could help to recognize this case and then readjust the dispensing parameters pressure and time. Machine vision techniques can therefore be used to evaluate a change of the droplet size and set the parameters in a closed loop control.

Recording one picture before and one after dispensing are the basis for this task. The following image processing steps include discarding the color information, equalization of brightness and a final subtraction of the two images (Fig. 6). The droplet size can then be evaluated by simple white pixel counting in the region of interest or with the help of a more advanced snake algorithm.

4. Anisotropic tape

The 3M *Z*-axis adhesive film 5552R [5,6] is a heat bonded film that allows anisotropic electrical connection only in the *Z*-axis through the film. This film contains gold coated conductive polymeric spheres with an average diameter of 5 μm mixed in an adhesive matrix. While the curing process where the film is cured under high temperature and pressure is applied to the film, these particles form an electrical interconnection only in the *Z*-axis through the film and allow fine pitch (<100 μm) flex to LCD interconnections. A typical application nowadays is the flex to LCD interconnection in a large number of cellular phones. No information could be obtained from 3M if this film can be used for assembly of MEMS devices.

As it is suitable for fine pitch bondings with a minimum overlap area of 0.015 mm^2 and a low thickness of just 19 μm it was chosen for bonding the triaxial force sensor to a flexible circuit.

The overall assembly process consists of four steps. In the first step the clean flexible circuit substrate is placed on the hotplate. A suitable piece of 3M film (3 mm × 3 mm) is then placed over the electrical contacts (Fig. 7A) and heating up to 60 °C tacks the tape to the substrate (Fig. 7B). In the second step the sensor is picked up, aligned and placed on the tape (Fig. 8A). It is followed by the curing of the film (Fig. 8B), which starts with heating up the hotplate to 150–160 °C. The sensor is held with a force of 100 mN on the flexible circuit as long as the temperature is below 110 °C. As soon as the temperature is higher, the force is increased to 6 N and maintained for approximately 20–40 s (Fig. 9A and B). When the 6 N force is applied the electrical contacts are established (Fig. 9C) and so the resistance measurement between the tracks on the flexible circuit show values in the range of 700 Ω–1 kΩ (typical value of one piezoresistor). After the curing time of about 20–30 s the heating element of the hotplate is switched of, the hotplate cools down and the force is released.

5. Sensor characterization

For characterization of the successfully assembled MEMS force sensors a set up similar to the one in Ref. [2] is used. Here the core component is a six axial load cell [ATI NANO 17 F/T, Apex, USA]. The following schematics (Fig. 10) is used

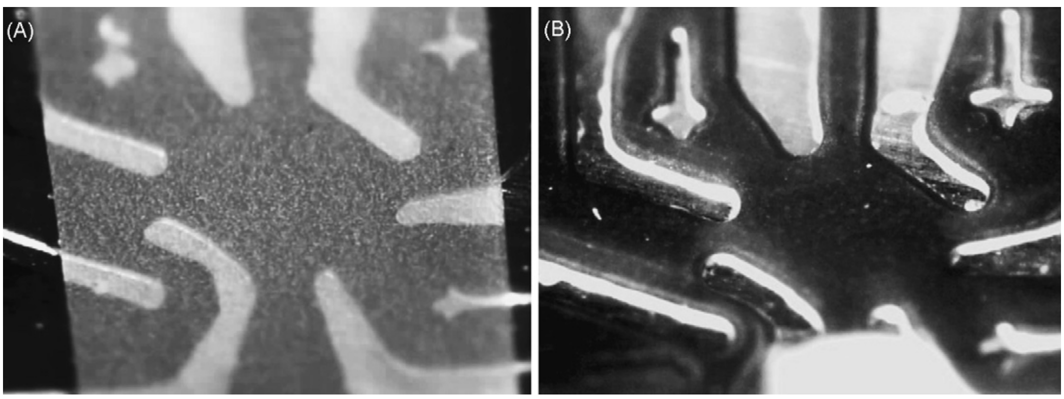

Fig. 7. (A and B) Tacking the film to the substrate.

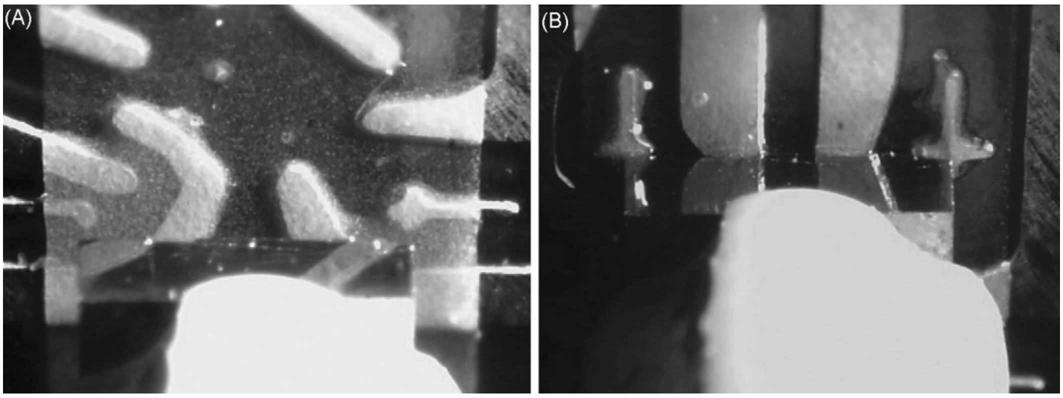

Fig. 8. (A and B) Placing and curing.

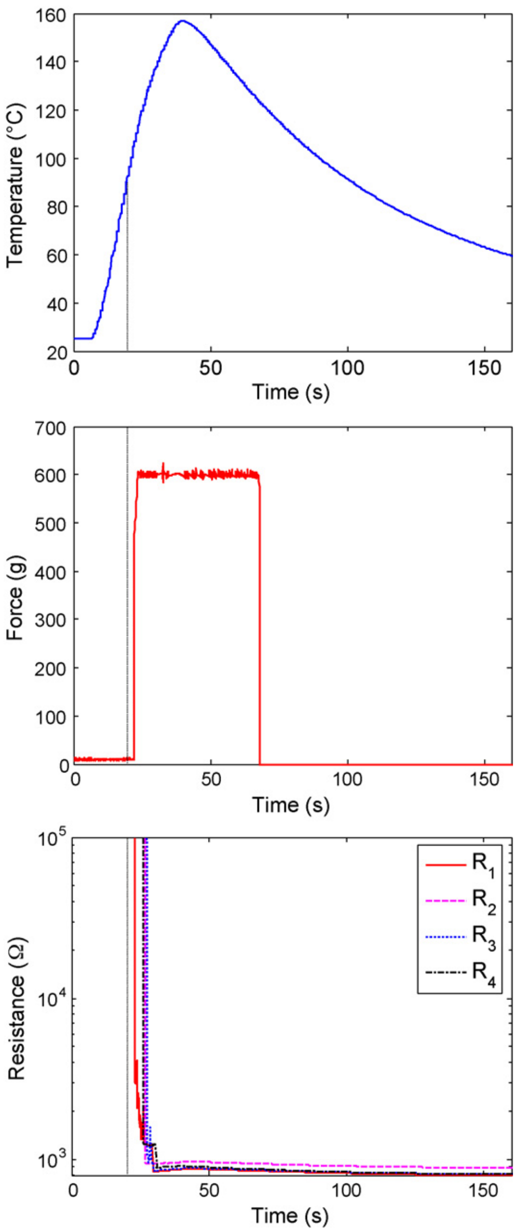

Fig. 9. (A–C) Temperature, force and resistances during the assembly process.

to acquire three digital signals proportional to the normal force (ADC Normal Loadings) and the tangential forces (ADC Tangential Loadings *x*, *y*). For normal loadings the sensor signal is processed in a quarter bridge configuration, for tangential loading in half bridge configuration. The Analog Devices AD7730 ADC used for the electronics is a programmable 24 Bit sigma delta ADC with an input range of ±80 to ±10 mV. No additional amplification of the signals is necessary. Furthermore, the ADC offers two fully programmable digital filters suitable to remove high frequency noise and set a suitable −3 dB frequency.

The ADC's serial peripheral interface (SPI) interface is directly linked to a PC printer port. The SPI protocol emulating software is programmed in National Instruments Labview 7.0 under Windows XP.

To characterize the sensors normal force and tangential force output voltage responses were recorded. For normal loadings (Fig. 11) the sensitivity is 20 mV/N. Applying a tangential force Fx (Fig. 12) results in a signal reading in ADC 2 for tangential forces in *x* direction, while the signal readings from ADC 3 (tangential readings in *y* direction) stay largely unaffected.

6. First results

Four sets of 10 sensors each were mounted with either the 3M film, solderpaste or one of the two Ablestick glues (Table 1).

Each sensor consists of four piezoresistors, so the result can be measured in the number of working resistors (0–4 correctly working). Very little successful bondings were achieved with the glues. There the contacts broke off during the cooling phase. The electrical contacts achieved by the soldering process showed a resistance below 0.5 Ω, but were mechanically fragile. Light bending of the flexible circuit forced the sensor contacts to break off. The 3M film 5552R showed best performances in this category together with a reliable mechanical bonding. Contact resistances below 0.5 Ω were achieved. Additionally, the overall process time is very low in comparison to the one needed for assembly with glues.

This process allowed the miniaturization of the overall dimensions of the sensorized device as no additional silicon support is used anymore. The output is a mechanically and electrically robust assembly. The first prototypes allowed the

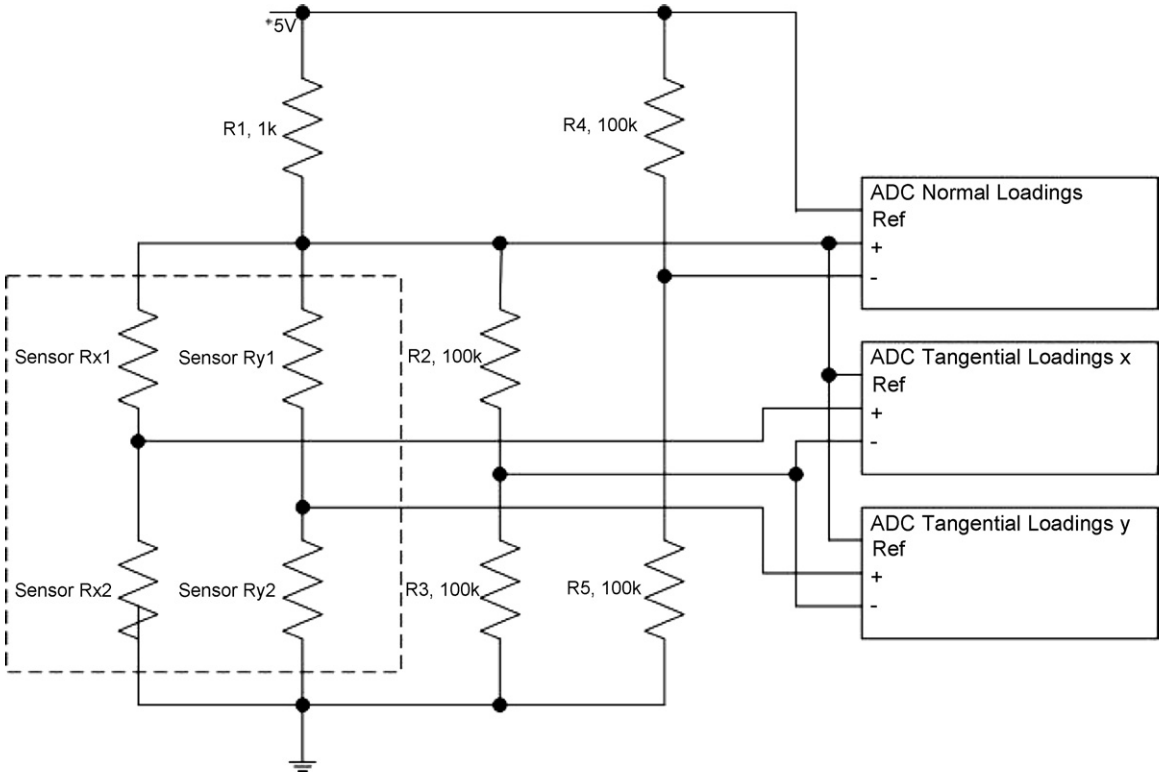

Fig. 10. Electronic circuit layout.

miniaturization of the sensorized cutting reported in Ref. [7]. The overall outer diameter of the device could be reduced from 7 to 3 mm which makes it suitable for a novel surgical tool for (robotic aided) endoscopy (Fig. 13A and B). This triaxial force sensor is the core component in a tactile skin prototype [8] and so represents another application, where this assembly process was one of the major key developments. This prototype showed the feasibility of an artificial skin with integrated force sensors to allow a kind of artificial palpation with slip/stick detection, which is a important task in the gripping force control of an artificial hand.

For such an artificial skin an array of sensors is required. To allow an assembly of more than one sensor the active part of

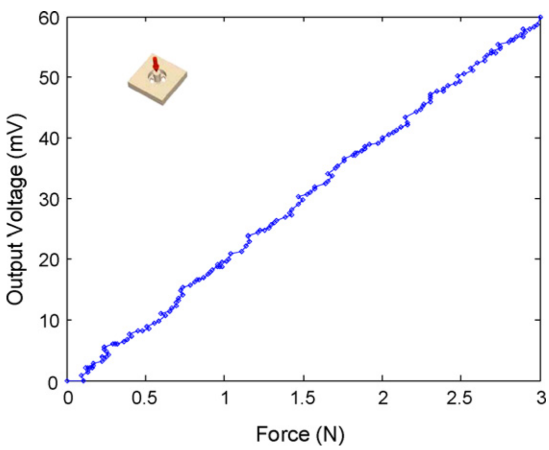

Fig. 11. Output signal for normal loadings.

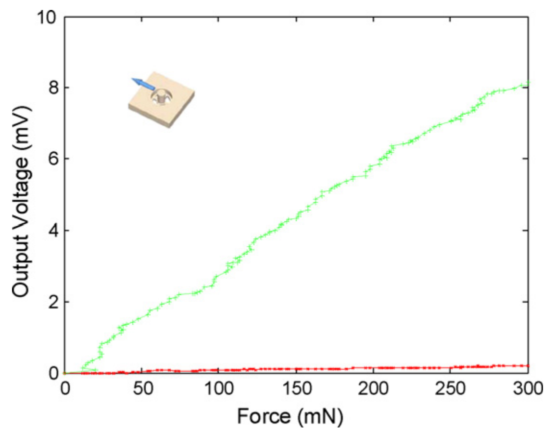

Fig. 12. Output voltage for tangential loadings.

Table 1
First results and comparison

	5552R	Soldering	84-1LMISR4	826-1DS
Assembly time (min)	~7	~5	~5	~5
Curing process duration (min)	1	1.5	60	30
Total (min)	8	6.5	65	35
Curing temperature (°C)	160	220	175	150
Outcome (Testset = 10)				
4/4 resistors ok	8	4	0	1
3/4 resistors ok	1	2	1	0
2/4 resistors ok	0	2	1	1
1/4 resistors ok	1	1	4	3
0/4 resistors ok	0	1	4	6

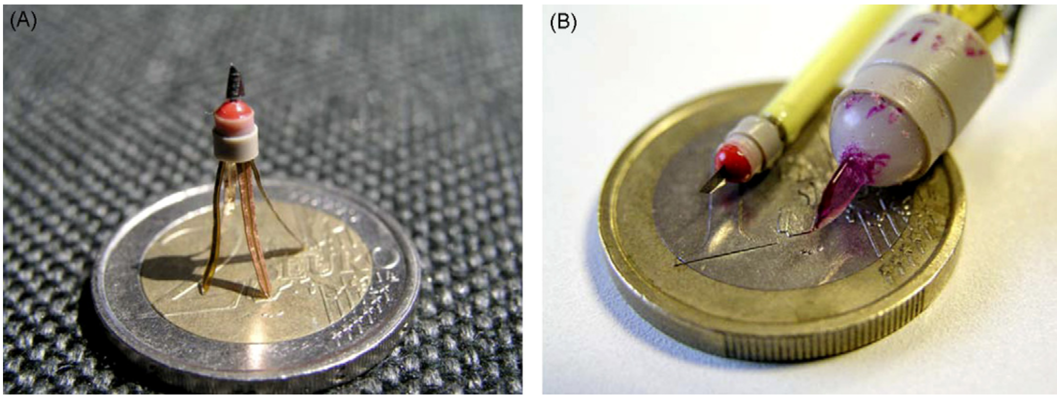

Fig. 13. (A) Sensorized cutting device for surgical applications with the triaxial force sensor as core component. The flexible circuit tracks that come out of the sensor housing lead directly to the MEMS sensor which is placed under the nylon ball encapsulated in soft polyurethane. (B) Direct comparison of the miniaturized tool (left) with the previous one (right) demonstrates the advantage of a direct assembly of the force sensor on a flexible circuit.

the hotplate was miniaturized allowing heating up of just the small area under the sensor. This allows assembly of one sensor after the other. First prototypes with three sensors on one flexible circuit were successfully manufactured.

7. Future work

Now that a suitable bonding material is found and an assembly process is defined the next step is a half automatisation of the assembly station. A fully automatisation is in principal feasible but actually not needed, as the authors work is more oriented to research and prototyping than product development, thus high flexibility is more important than high throughput.

Manual assembly steps will be placing the flexible circuit on the hotplate, cutting and alignment of a suitable piece of conductive film. The sensor itself is then placed manually somewhere on the flexible so that it can be picked up by the gripper. The half automatisation will mainly include automatic alignment of the sensor on the flexible substrate followed by the curing process. To enable automatic alignment machine vision techniques will be used. Therefore, a novel suction gripper was designed with an integrated microcamera to allow a plan view on the sensor without perspective distortion (Fig. 14). The gripping part consists of a transparent plexiglass support with an integrated channel for applying the air suction and a polyetheretherketone resin (PEEK) tube with an outer diameter of 1.4 mm. PEEK was chosen as it can withstand the temperature of the curing process. For automatic alignment the *xy* stage will be upgraded with servo drives.

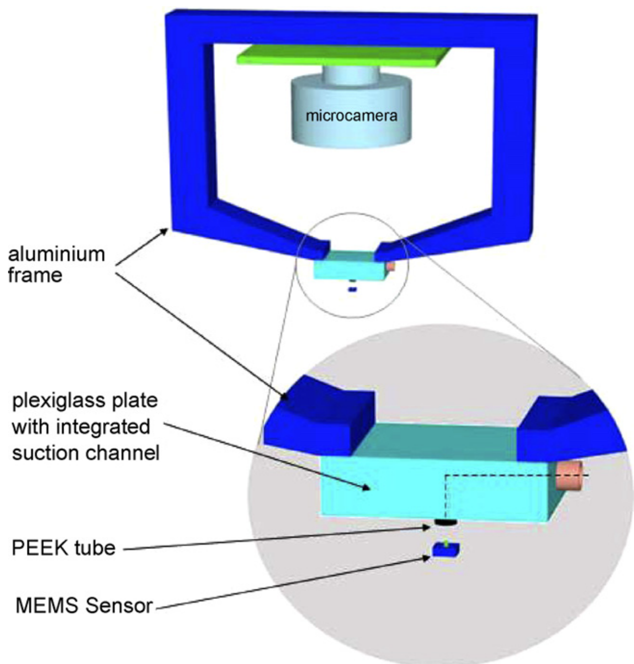

Fig. 14. Design of the new vacuum gripper with an integrated microcamera.

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Biographies

Arne Sieber finished his studies of biomedical engineering in 1999 at the Technical University of Graz, Austria. From 1997–2001 he gained his first industrial research experience at AVL Medical Instruments in Graz, Austria. The next 4 years he worked for Roche Diagnostics in R&D of electrochemical and optical sensors. He finished his PhD about electrochemical sensors in 2002. He is currently working as a researcher in R&D of Microsensors and Actuators for ARC Seibersdorf research GmbH. Within a knowledge transfer program, he has been part of a research team for the last year at the CRIM Lab of Scuola Superiore Sant'Anna in Pisa, Italy.

Pietro Valdastri received his Laurea Degree in electronic engineering (with Honors) from the University of Pisa in February 2002. In the same year he joined the CRIM Lab of the Scuola Superiore Sant'Anna in Pisa as a research assistant. In January 2003 he started his PhD in bioengineering at CRIM Lab. Main research interests are in the field of implantable biotelemetry, MEMS-based biosensors, and swarm robotics. He is working on several European projects for the development of minimally invasive biomedical devices.

Keith Houston completed his bachelor and research masters degree in mechanical engineering at the University of Limerick in Ireland in 2002. After graduation he joined the precision engineering industry in Northern Ireland until 2004 when he joined the CRIM Lab of Scuola Superiore di Sant'Anna to begin a PhD in teleoperation of micromanipulation processes. He is also involved in micro-robotics and design of micromanipulation tools.

Arianna Menciassi (MS, 1995; PhD, 1999) joined the CRIM Lab of the Scuola Superiore Sant'Anna (Pisa, Italy) as a PhD student in bioengineering with a research program on the micromanipulation of mechanical and biological micro-objects. The main results of the activity on micromanipulation were presented at the IEEE International Conference on Robotics & Automation (May 2001, Seoul) in a paper titled Force Feedback-based Microinstrument for Measuring Tissue Properties and Pulse in Microsurgery, which won the ICRA2001 Best Manipulation Paper Award. In the year 2000, she was offered a position of assistant professor in biomedical robotics at the Scuola Superiore SantAnna and in June 2006 she obtained a promotion to associate professor. Her main research interests are in the field of biomedical microrobotics, biomimetics, microfabrication technologies, micromechatronics and microsystem technologies. She is working on several European projects and international projects for the development of minimally invasive instrumentation for medical applications and for the exploitation of micro- and nano-technologies in the medical field.

Paolo Dario received his Dr. Eng. Degree in mechanical engineering from the University of Pisa, Italy, in 1977. He is currently a professor of biomedical robotics at the Scuola Superiore Sant'Anna in Pisa. He has been visiting professor at Brown University, at the Ecole Polytechnique Federale de Lausanne and at Waseda University. He was the founder of the Advanced Robotics Technologies and Systems (ARTS) Laboratory and is currently the Coordinator of the Center for the Research in Microengineering (CRIM) Laboratory of the Scuola Superiore Sant'Anna, where he supervises a team of about 70 researchers and PhD students. He is also the Director of the Polo Sant'Anna Valdera of the Scuola Superiore Sant'Anna. His main research interests are in the fields of medical robotics, biorobotics, neuro-robotics and micro/nanoengineering. Specifically, he is active mainly in the design of miniature and microrobotics systems for endoluminal surgery, and in advanced prosthetics. He is the coordinator of many national and European projects, the editor of two books on the subject of robotics, and the author of more than 200 scientific papers (90 on ISI journals). He is editor-in-chief, associate editor and member of the Editorial Board of many international journals. He has been a plenary invited speaker in many international conferences. Prof. Dario has served as President of the IEEE Robotics and Automation Society in the years 2002–2003, and he is currently Co-Chair of the Technical Committees on Bio-robotics of the same Society. Prof. Dario is an IEEE Fellow, a Fellow of the European Society on Medical and Biological Engineering, and a recipient of many honors and awards, such as the Joseph Engelberger Award. He is also a member of the Board of the International Foundation of Robotics Research (IFRR). He is the General Chair and Program Chair of the 1st IEEE RAS/EMBS Conference on Biomedical Robotics and Biomechatronics (BioRob 2006), and the General Chair of the IEEE International Conference on Robotics and Automation (ICRA2007).