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Separation of extremely miniaturized medical sensors by IR laser dicing

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A microchip separation process operating by pulsed-wave IR laser irradiation was applied to microviscosimeters that are intended to operate as glucose sensors for continuous monitoring of blood sugar levels in diabetics. After its technological preparation the sensor should no more dry up, since the retreating water would stick a movable cantilever to the ground plate and thereby plastically deform the sensor's micromechanics. The cooling-free IR laser dicing process was thus chosen for the separation. It is shown that virtually particle free dices with lateral dimension down to some 100 µm could be prepared. The process is concluded to enable the dry, fast and clean separation of MEMS devices.

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Keywords: MEMS, glucose sensor, Si wafer, stealth dicing

1. Introduction

The continued scaling of microelectronic devices and microsystems will enable the development of innovative biomedical and biotechnological systems that are characterized by an improved comfort for patients and reduced costs for the measurement of medical parameters [1]. In particular for the increasing point-of-care diagnostics so-called biomedical microelectromechanical systems (BioMEMS) are urgently requested that do not determine the health-relevant parameters at the clinic or practice, but in the patient's world of living. Various concepts are currently under development that aim at the transformation of biochemical information into microelectronic circuitry. In most cases, these concepts rely on the immobilisation of functional biomolecules on technical surface of semiconducting materials like silicon in order to establish compatibility with the dominating CMOS technology (complementary metal-oxide-semiconductor). The immobilisation is often performed via silane-based covalent bonding [2,3], but also electrically assisted processes [4] or the physical adsorption on nanotemplated silicon surfaces [5,6] are under investigation. Further principles of transformation rely on the modification of physical properties of the solution under investigation like viscosity [7], optical turbidity [8] or other parameters, for the determination of which BioMEMS may advantageously apply.

One of the most important metabolites of the human body is β-D-glucose. The transport of glucose into the cell as initiated by insulin and performed via glucose transporter protein GLUT4 is well known to be disturbed in case of *diabetes mellitus*, such that patients suffer from deviations of glucose from its normal concentration range lying between 3.6 and 6.1 mM in blood. The impairments to health like vascular damage, decline of sight and many others could be effectively reduced by a continuous control of blood sugar levels. Numerous attempts for the development of improved glucose sensors have been endeavoured in the last decades and almost no physical effect with relation to glucose concentration has been omitted to be tested for solving the problem [9, 10]. We report here about the microfabrication of an extremely miniaturized glucose sensor that shall continuously operate by the principle of affinity viscosimetry [7] and has been constructed as a microviscosimeter [11]. The affinity assay does not rely on the chemical reaction of glucose, but operates simply by its affinity binding to the plant protein concanavalin A (Con A). For this purpose, a sensoric fluid that encompasses of concanavalin A and the glucose polymer dextran is set into equilibrium with glucose. Since both saccharides, glucose and dextran, compete for the affinity binding to Con A, the degree of macromolecular cross linking between Con A and dextran is controlled by the glucose concentration and thus is the viscosity of the fluid. The suitability of this approach for continuous glucose monitoring has already been demonstrated in a clinical study by use of a measurement system deriving the viscosity change from the pressure decrease occurring in a steady-state flow of sensoric fluid through a dialysis fiber [12]. However, sensor systems based on this technical approach still exhibited relatively large spatial extensions and hardly made use of the miniaturization potentials of microelectronics and microsystem technology.

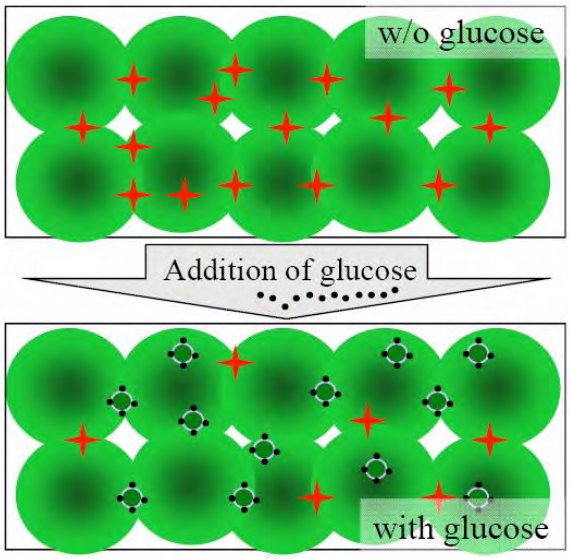

Fig. 1. Principle of affinity viscosimetric measurement of glucose. Large circles symbolize macromolecular dextran (a glucose polymer), while the small stars and balls stand for concanavalin A, a lectin of 26.5 kDa molecular weight consisting of 237 amino acids. Con A forms affinity bonds with both dextran and glucose. The concentration of glucose thus affects the macromolecular cross linking between Con A and dextran and, therefore, the viscosity of the liquid.

The task was thus to construct and prepare a microviscosimeter as a microelectromechanical systems (MEMS) that can be filled with sensoric fluid and enables the transformation of glucose concentration into viscosity. It has to be considered, however, that the final fabrication step in the processing of MEMS devices is not a simple task, since the relative significance of surface tensions in aqueous solutions increases with decreasing size of the structures to be processed. One of the consequences is that the meniscuses formed during evaporation or drying may cause stiction and a plastic deformation of the movable MEMS components, which may lead to a complete destruction of the sensor. Standard processes of microelectronic fabrication like usage of a cooling liquid for die separation by sawing thus have to be avoided. The otherwise trivial question of separating the sensor dice from the wafer accordingly becomes a serious obstacle in the processing of BioMEMS for microfluidic applications that may not easily be circumvented with conventional methods. It will be reported in this work about the separation of extremely miniaturized glucose sensor MEMS by IR laser irradiation, which is also known as stealth dicing.

2. Experimental and results

The microviscosimeter was fabricated in the IHP clean room as a fully integrated MEMS on 200 mm Si wafers using a 0.25 µm BiCMOS technology [13]. The microelectronic sensor structure intended for the measurement of viscosity consisted of an electrically conductive and elastically bendable cantilever above a conductive ground plate, see Fig. 2. The cantilever is bending during operation by applying an electrical voltage between it and the ground plate, which is also associated with a capacity change of the cantilever-ground plate configuration. The microelectromechanical system has been constructed such that it allows for the determination of viscosity after introducing the sensoric fluid. The cantilever and ground plate were not fabricated from the silicon bulk material as usual in MEMS technology, but from metal layers of the Backend-of-Line stack in order to attain a sufficiently high electrical conductivity. Since, additionally, a high corrosion resistance and biocompatibility of the structures exposed to the human tissue were required, both the cantilever and ground plate were completely prepared from TiN [14]. The complete sensor chip including the micromechanical cavity and electronic circuit occupied an area of less than 1.3 × 0.4 mm.

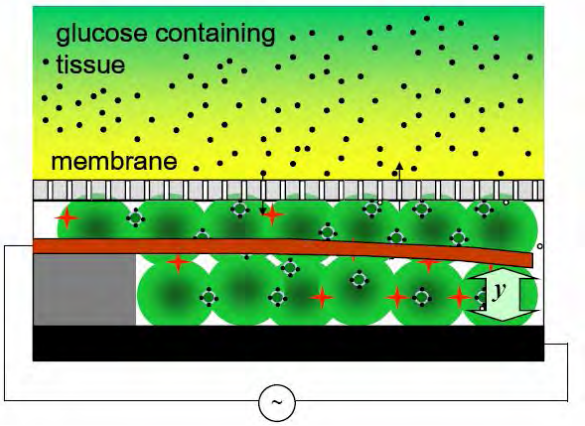

Fig. 2. Schematics of microelectromechanical viscosimeter with electrically conducting cantilever and ground plate. The glucose concentrations in the tissue and in the MEMS cavity equilibrate through a semipermeable membrane that confines the macromolecules to the cavity. The viscosity of the sensoric fluid within the cavity is determined by the glucose concentration and is measured from the time it takes for the cantilever to reach a defined position. In the fabricated sensor chips the height of the cantilever above the ground plate amounts to 2.5 µm, while the length of the cantilever is in the 150 µm range [11].

Si wafers were thinned to a thickness of 150 µm after delivery from the clean room. Only subsequently, the moveable cantilevers were etched free from the interlayer dielectric by a HF containing etching solution and a following critical point drying with CO_2 (Automegasamdri-916B, Series C, Tousimis research corporation). Consequently, the sensor dies were to be separated from the wafer, for the process of which a contact with liquid media has to be avoided. It was thus made use of the stealth dicing method introduced only recently, where the chips were separated in a two-step process by firstly inscribing the dicing lanes by IR laser irradiation and secondly applying an in-plane tensile stress to induce controlled fracture. Both process steps were carried out by placing the 150 µm thin Si wafers on an expandable tape and introducing them for laser irradiation into the ML 200 tool of Accretech company. This system operates with a pulsed IR laser beam (λ = 1064 nm, 100 kHz) that is directed normally upon the wafer for a number of scans. Dicing lanes were to define in the chip layout before processing and, ideally, should represent 40 µm broad lines free of devices and test structures.

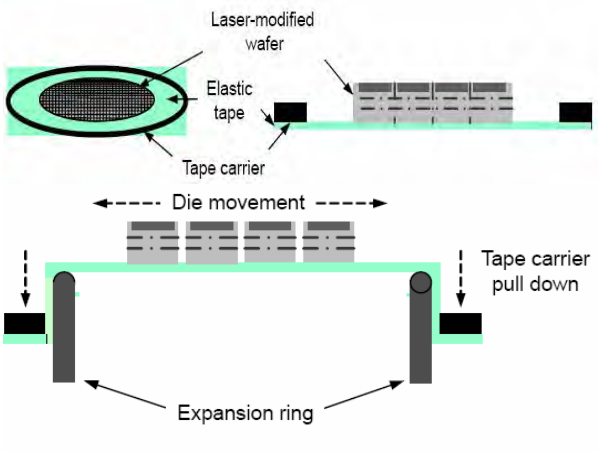

Fig. 3. Principles of the two-step stealth dicing process operating by (top) multiple laser irradiation and (bottom) subsequent chip separation.

The absorption coefficient of Si is strongly varying in the vicinity of the used wavelength of 1064 nm, since it is close to the band edge of 1110 nm. In addition, the absorption sensitively depends upon the degree of doping for the applied wavelength [15]. Accordingly, the deposition depth at which the major part of beam energy is absorbed may carefully be adjusted by the focus of the laser beam. A volume of some $(10\ \mu m)^3$ in the focus of the beam is heated to temperatures of some 1000 K within a time span of ns for the beam energies used in the stealth dicing process [16]. Microscopically small irregularities are thereby introduced in the Si bulk below the wafer surface that exhibit the shape of a candle flame. A modified zone that extends beneath the dicing lanes is formed by multiple scans of the IR beam and variations of the focus depth. The crystallographically disrupted areas act as crack initiation sites along which the wafer would preferentially separate during mechanical loading. For this purpose, a tensile stress is introduced in the second step of the stealth dicing process by radially expanding the supporting tape and cleaving the Si wafer along the dicing lanes. Fig. 3 displays the schematics of both process steps.

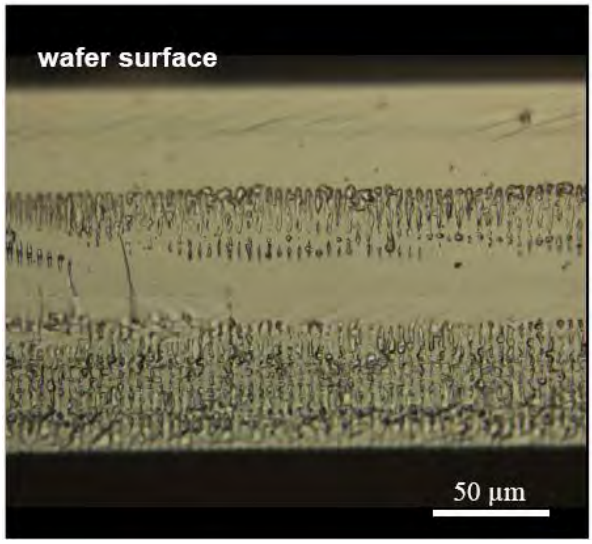

Fig. 4. Cross section micrograph of separated chips showing the fracture initiation lines caused by four IR laser scans with different focal depths (white bar 50 µm). While the foci of the first three lines were so closely spaced that the different lines merge to one common disruption zone at the bottom of the wafer, the final fourth line separately appears at about 60 µm below the wafer surface.

An optical microscope cross-sectional view showing the disrupted zone after fracture of the sensor chip prepared by multiple scans with four different focal depths is displayed in Fig. 4. The different belt-shaped disruption zones are clearly recognized beneath the surface of the 150 µm thick wafer. The pulsing of the laser is manifest from the lateral distance between single "candle flames". The scanning speed of the laser beam upon the surface can be devised from their distance of about 4 µm and the pulse rate of 100 kHz and is realized to amount to 40 cm/s. For a preferably particle-free separation of the wafer on the supporting tape, the cleavage should begin at the bottom and extend to the top of the wafer. Therefore, the focal depths where chosen such that three deposition depths yielded disruptions close to the bottom up to a height of about 60 µm, while only the fourth scan generated a further line at a medium depth.

A certain complication was related to the fabrication of sensors in the framework of IHP's multiproject wafer shuttle. Accordingly, other circuits than only glucose sensors were prepared on the same chip. The full 200 mm wafer was devided into 26×16 mm large rectangular chips and the surface occupied by BioMEMS structures

amounted to only 1.5 % of the whole wafer area. Those parts of the wafer unrelated to glucose sensors were fully covered by nontransparent metal layers, which was of relevance to the separation process because they acted like mirrors to the IR laser beam. Therefore, no beam energy could be deposited under those areas and thus no initiation sites for cracking could be inscribed. However, in spite of these complications, the stealth dicing process could be shown to enable a separation of the very small sensor structures.

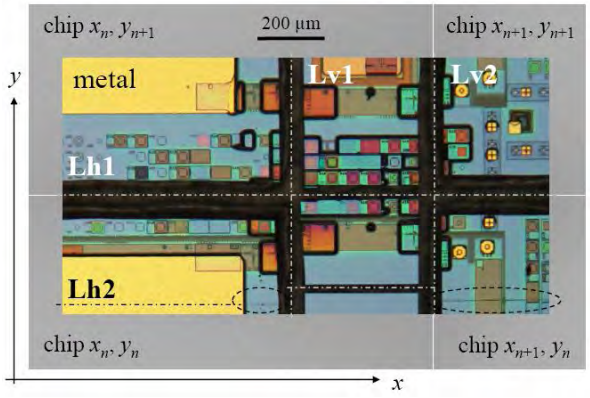

Fig. 5. Micrograph of separated chips after the expansion process, top view, with black areas representing kerf grooves (scale bar on top of the figure has a width of 200 µm). The laser beam was guided four times along every dicing lane. The deposition of laser energy below the wafer surface, however, could only be achieved beneath areas that were not covered by metal, where the laser radiation was reflected. A part of the kerf grooves did thus not exhibit a continuous cleavage as is seen for the horizontal line Lh2. Metalized areas thus caused certain asymmetries to occur for separated dies and kerf grooves of different width.

Fig. 5 displays an optical microscope view on a wafer section, where four chip edges met, after the expansion step. The wafer can be seen of having been cleaved into various rectangles caused by the expansion of the underlying tape. On the one hand, the figure hardly shows any particles generated from the process. This point is of essential importance for the preparation of BioMEMS intended to serve in aqueous solutions, because the particles might be swept away during operation and cause a deterioration of active MEMS parts. On the other hand, it can be recognized from the figure that the stealth dicing process caused a complete cleavage along the metal free chip edges. This is clearly demonstrated by horizontal line Lh1 and vertical line Lv2. Also the vertical line Lv1 exactly cleaves the chip along the intended dicing lane, since no metal layers could cause a back reflection of the impinging beam. In addition, the few devices and test structures crossing Lv1 left the cleavage plane mainly unaffected and were simply cut during the expansion process. It can be recognized, however, that no cleavage was induced along the complete horizontal line Lh2, but only along a limited fraction.

The interesting (and expected) observation can be made that hardly any effect of the laser beam was introduced into the metallised areas. The inscribed dicing lane may only be recognized in adjacent areas covered by transparent oxide (dashed circle), albeit the tape expansion did not cause a separation. A cleavage can be observed, however, along the horizontal line Lh2 in the middle part of the figure, where the two vertical line were only 360 µm spaced apart and remained unaffected by the full-area metallization of the surrounding. This was the interesting section of the chip, since all prepared BioMEMS sensors were positioned between Lv1 and Lv2, from where they could safely be taken for further processing. The phenomena just described for a small area were equally observed on the full wafer surface. It can be concluded from the presented results that the stealth dicing process has successfully been applied for the separation of BioMEMS sensors even in the difficult case of multiproject wafers partially covered by reflecting metallic areas.

3. Conclusions

To summarize, the application of the stealth dicing process to the separation of extremely miniaturized MEMS sensors for affinity viscosimetry has successfully been demonstrated. Less than 1 mm^2 small BioMEMS could be prepared from 200 mm Si wafers thinned to 150 µm by a process completely avoiding cooling liquids. The separation could even be demonstrated for the challenging case that a large fraction of a multiproject wafer was covered by a closed metallization. The stealth dicing process might thus be considered an enabling technology for the preparation of BioMEMS or other integrated sensors, where a contact of the mechanical structures with liquid media during preparation has be to avoided.

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