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MEMS techniques applied to the fabrication of anti-scatter grids for X-ray imaging

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Abstract

This paper reports a promising method for the fabrication of lead collimators for X-ray radiology applications. The fabrication method is based on arrays of macropores etched into a silicon wafer using an electrochemical process. The macropores are filled with lead and the silicon substrate is removed subsequently. The macroporous silicon structure thereby acts as a sacrificial layer. The use of MEMS techniques enables us to decrease the size of the grid structure by one order of magnitude compared to conventional collimators, thus increasing the optical resolution of the X-ray system.

Keywords: MEMS techniques; Anti-scatter grid; Macroporous silicon; Sacrificial layer

1. Introduction

In contrast to scientific X-ray techniques, e.g. single-crystal diffractometry, in medical X-ray diagnostics all information is contained in the intensity distribution of the primary radiation. The unavoidable scattered radiation is unwanted because it decreases the signal-to-noise ratio and thereby the resolution of the X-ray image. Therefore, in radiology, a collimator located between the patient and the photographic plate is used to absorb scattered X-ray photons, which otherwise would blur the image [1]. Such collimators are termed anti-scatter grids. State-of-the-art grids consist of alternating layers of lead as absorbing medium and paper or aluminum as transparent medium [2–4]. Due to the fabrication process for which these layers are mechanically stapled and glued together the achievable number of layers per millimeter is about 3–6. Due to this limitation the anti-scatter grid has become a limiting factor for the image quality of today's radiology systems [5]. These drawbacks can be circumvented by a new fabrication process for anti-scatter grids based on macroporous silicon. This process enables us to increase the number of absorbing elements per millimeter by one order of magnitude.

2. Fabrication process

The fabrication process combines a mould prepared by semiconductor manufacturing techniques with lead casting. A schematic view of the fabrication process of the new silicon anti-scatter grid (in the following denoted SIGRID for silicon grid) is given in Fig. 1. First etch-pits in a desired pattern are formed on the silicon wafer surface by photolithography and subsequent alkaline etching (a). These etch-pits serve as initiation sites for the subsequent electrochemical etching process which generates straight pores of 600 μm depth and 8 μm diameter (b). The etching technique and its different applications have been described in detail elsewhere [6,7]. Next a 100 nm silicon nitride layer is deposited onto the pore walls by chemical vapor deposition (c). The homogeneity of the silicon nitride layer is decisive for the success of the process, because it serves as an etchstop layer in the subsequent chemical etch-back of silicon. The deposition of the silicon nitride layer is followed by lead casting of the silicon mould. Lead was chosen as absorbing component not only because of its physical properties — namely a very high absorption coefficient for X-ray radiation in the radiology energy regime — but also because of process simplicity and economical efficiency, respectively. Lead can be easily deposited into the pores using a die casting process. This is in contrast to other high absorbing materials such as tungsten, gold or platinum, for which, due to their high melting points, a CVD-process is the common deposition method. Metal alloys are no alternative, because they generally show a lower absorption coefficient for X-ray radiation than pure elements due to structural effects (e.g. a lower packing density and therefore a lower density as well as symmetry reductions due to ordering processes).

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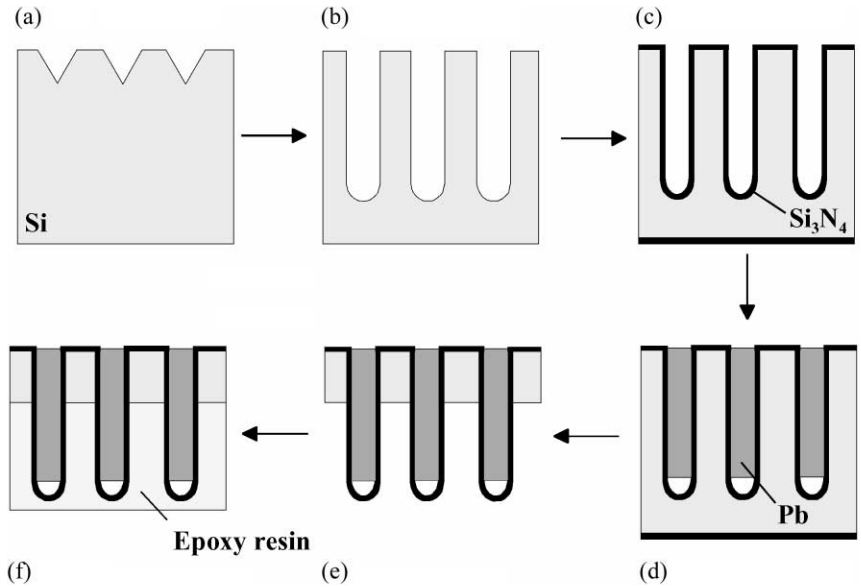

Fig. 1. Schematic view of the fabrication process for the SIGRID: (a) lithography; (b) etching; (c) CVD-nitride; (d) lead casting; (e) etch-back; and (f) epoxy fill.

The experimental set-up for lead casting is schematically illustrated in Fig. 2. In order to obtain a sufficient filling of the pores, the sample wafer is first evacuated in a pressure chamber and heated up to the temperature of liquid lead by illumination. Under zero pressure the wafer is then immersed into the liquid lead. Then a pressure of 5 bar is applied, which is required to overcome capillary forces of the liquid lead in the micrometer size pores. The wafer is then pulled out of the liquid lead and the lead inside the pores is allowed to solidify under applied pressure. After the pressure in the tank has been reduced to ambient pressure the wafer is removed (d).

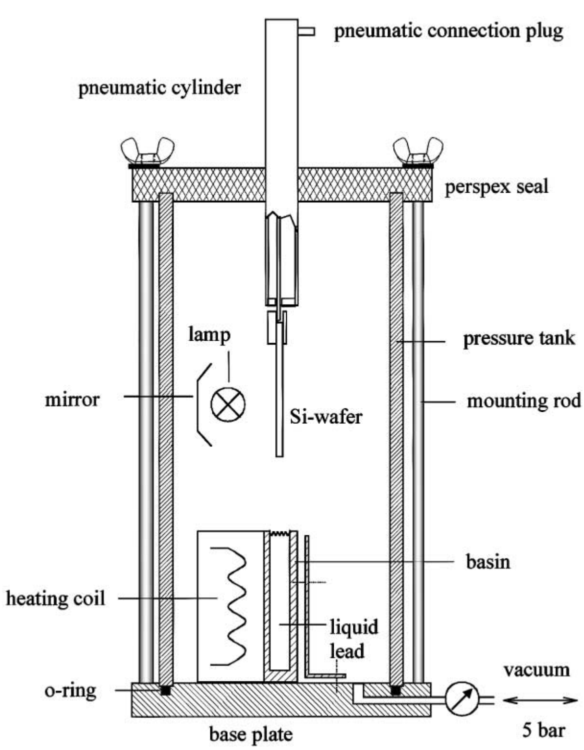

Fig. 2. Schematic view of the lead-casting apparatus.

For X-ray imaging in the low energy regime used for mammography (up to 30 keV) the silicon absorption is undesirably high. It is therefore desirable to remove at least part of the silicon. This can be done by etch-back the bulk silicon in hot potassium hydroxide (KOH) solution. Before immersing the sample into the KOH etchant, the silicon nitride layer on the wafer backside has to be removed. The silicon nitride layer inside the pores serves as an etchstop layer during this process (e). It, furthermore, acts as a mechanical support for the soft, free-standing lead pillars during drying after the etch-back. Unsupported, pure lead pillars would inevitably stick together due to capillary forces at the liquid–gas interface. By using this technique, about half of the total thickness of the bulk silicon wafer can be removed before the mechanical stability of the lead filled nitride pillars becomes critical. A SEM image of a sample at this stage of the fabrication process is shown in Fig. 3. Due to volume reduction of the lead during solidification, the pore tips remain free of lead, as can be seen in Fig. 4. In a last step, the fragile structure of the free-standing lead pillars is stabilized by an epoxy resin fill (f).

If a further decrease in the thickness of the remaining silicon layer is desired, the wafer can be etched from both sides. In this case the remaining silicon supports the free-standing lead pillars in the middle of their length. Such a simultaneous etching from the wafer front- and backside, however, turned out to be difficult because the removal of the silicon nitride layer from the wafer front surface (e.g. by wet chemical etching, CMP or plasma etching) has been found to either destroy the passivation layer within the pores or

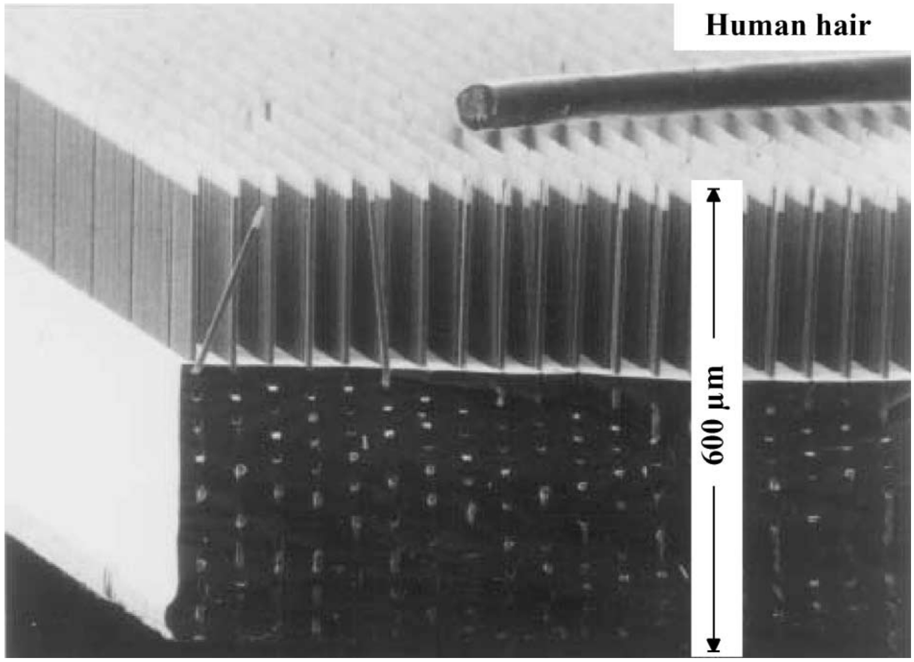

Fig. 3. SEM micrograph of the silicon wafer after etch-back of 265 µm bulk silicon. A hair is shown for size comparison. The lead pillars are arranged in lines using a close spacing within the lines (pitch: 16 µm) and a large spacing (pitch: 48 µm) between the lines.

induce defects that are subsequently etched preferentially in the KOH solution. Thus, a two-step etch-back process has been developed. In a first step, half of the thickness of the bulk silicon is removed by etching of the wafer in hot KOH solution from the backside. In a second step, the volume between the free-standing pillars is filled by an epoxy resin; afterwards the silicon nitride layer is removed from the wafer frontside by, e.g. CMP. Now the etch-back and resin fill procedure is repeated. The problem of preferential etching at defect sites now becomes neglectable, because the lead pillars are fixed by the epoxy layer. Moreover, this two-step technique allows to remove the silicon completely. The epoxy resin has to fulfill, however, strong demands concerning its chemical and mechanical properties. It must not only exhibit a sufficient chemical stability in hot KOH but needs to show a thermal expansion coefficient similar to silicon in order to avoid mechanical stress between the silicon and the epoxy resin during the hot KOH etch.

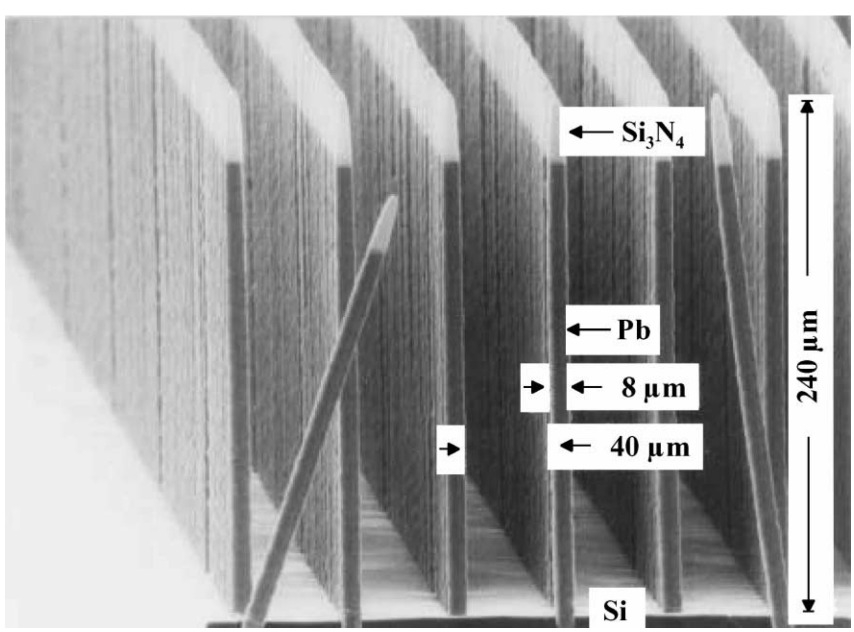

Fig. 4. SEM micrograph of the free-standing lead pillars. The front pillars appear distorted due to mechanical damage caused by cleaving of the sample.

3. Results

Simulations for the structure described above assuming an application as mammography grid (28 keV, Mo-Anode) have been carried out. The calculation has been split into two steps. First, the energy spectrum and the angular distribution of the scattered radiation have been calculated by means of a Monte–Carlo simulation. Then the transmission of the assumed grid has been simulated for the above calculated energy spectrum in dependence of the azimuthal and the polar angle. Finally, the results have been integrated to yield the resulting energy flux behind the grid. The simulation results not only allow us to determine the optimal grid geometry, but as well to compare the performance of a SIGRID of a certain geometry to conventional X-ray anti-scatter grids. As mentioned above, an X-ray anti-scatter grid should be highly transparent for the primary beam, but should suppress the transmission of scattered radiation significantly. The performance of an anti-scatter grid is thus mainly characterized by three parameters. The transmission of primary radiation T_P, the transmission of scattered radiation T_S, and the selectivity of the grid defined as the ratio T_P/T_S, respectively. For low energy applications the selectivity of the grid is mainly determined by the geometry of the pore arrangement. The best simulation results were obtained for a linear arrangement of pores as shown in Fig. 5. Comparing these results to the simulated values for conventional grids, the SIGRID is found to yield a comparable transmission of primary radiation, but a significantly reduced transmission of scattered radiation, thus increasing the selectivity of the grid.

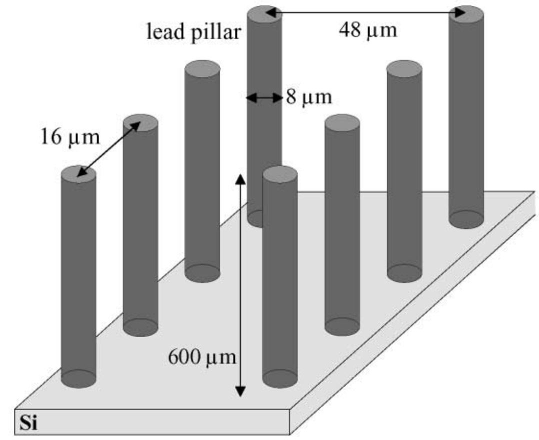

Fig. 5. Schematic view of the optimal grid dimension as determined by simulations of the transmission characteristic of various silicon anti-scatter grids.

The calculated results of transmission are partly supported by X-ray measurements using the standard measurement conditions for anti-scatter grids, as laid down in IEC-61953 [2] and DIN-6826 [3]. Measurements have been carried out using samples at different stages of the fabrication process, namely before (in the following denoted B-samples) and after the back-etch and resin fill process (called A-samples). B-samples, in which the lead pillars are still embedded in the silicon matrix, show a scatter transmission comparable to the simulated values, but a significantly reduced primary transmission. This is mainly due to shadowing effects. If the orientation of the lead pillars is not exactly parallel to the direction of the primary beam, the lead pillars will shadow each other which decreases the transparency of the grid. Such shadowing effects may be caused by a mis-orientation of the grid lines with respect to the direction of the primary beam or by a missing focusing of the grid (because of the divergence of the X-ray beam an anti-scatter grid has to be focused with respect to the X-ray source). Because of the high aspect ratio of the lead pillars small mis-orientations will effect the transmission much more than in conventional grids. To partly circumvent these problems, a self-focusing grid geometry in which the pores are arranged in radial lines emerging from a focus point is currently under investigation (Fig. 6). Measuring A-samples in which the silicon has been removed completely and replaced by an epoxy resin, the primary transmission is still found to be too low. The scatter transmission, however, is increased by a factor of 3 compared to the simulation results. This may be caused by local distortions of the lead elements (and thereby of the ideal grid geometry) that most probably originate from stresses between the epoxy resin and the silicon substrate during thermal cycling between room-temperature and hot KOH (80°C) or from a volume reduction of the epoxy resin

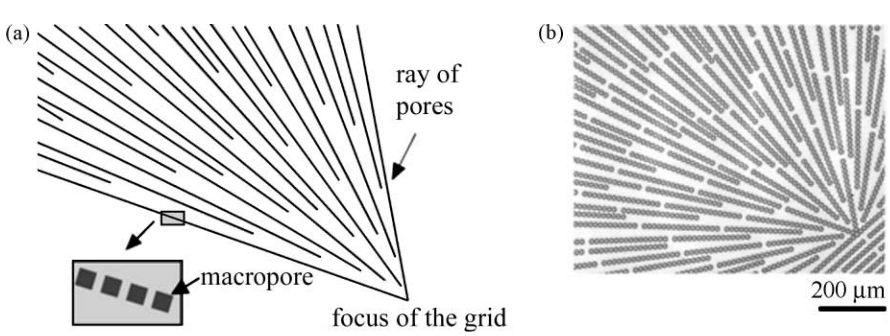

Fig. 6. (a) Schematic view of the self-focusing grid geometry and (b) optical micrograph of the developed lithographic mask. The pores are arranged in radial rays emerging from a focus point.

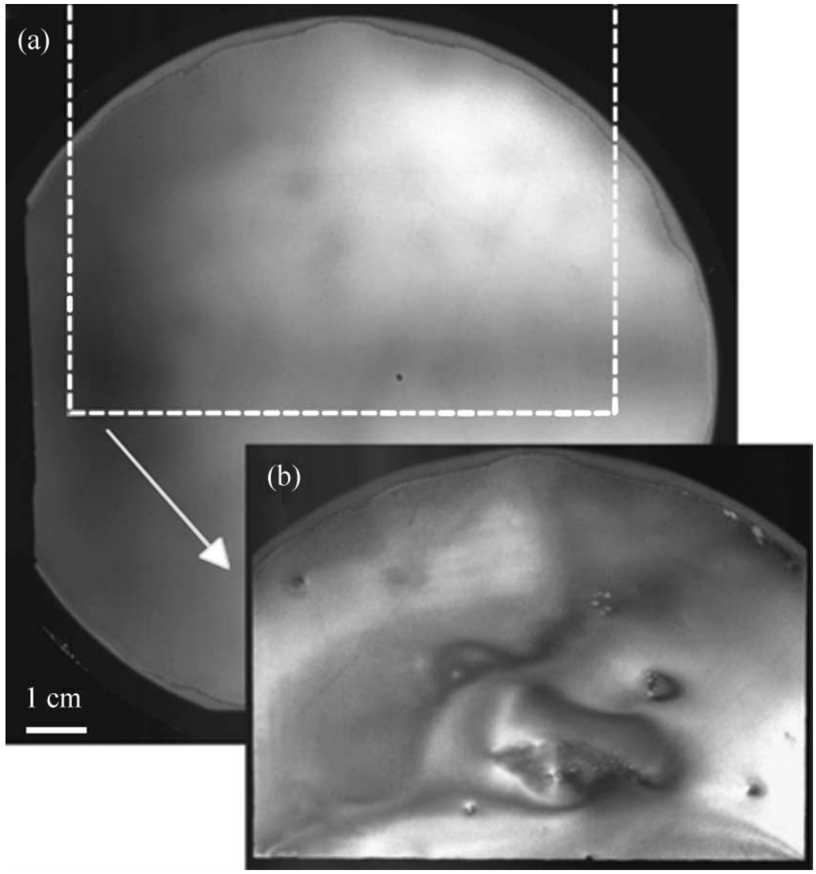

Fig. 7. X-ray images of a silicon anti-scatter grid (a) before and (b) after the back-etch and resin fill process. The homogeneity of the original sample (a) is destroyed due to stress effects during etch-back.

during hardening. These local distortions can be seen in X-ray images of the new anti-scatter grids as contrast inhomogeneities (shown in Fig. 7). Since an X-ray image yields a projection of the light-absorbing lead elements into the plane of investigation, the distortion of the lead pillars can be directly observed in optical micrographs of the X-ray image. Examples of such distortions are shown in Fig. 8.

Though the SIGRID so far does not satisfy the requirements concerning homogeneity — X-ray images of conventional grids show a homogenous grey-tone over the full size of the grid — the X-ray images of Fig. 7 show that the lines of lead pillars, as shown in Figs. 3 and 4, respectively, are not resolved by the naked eye due to their narrow spacing (48 μm). This is in strong contrast to conventional grids (spacing: 340 μm) which have to be moved during the exposure in order to avoid imaging of the lead lines (Fig. 9). Due to their tight spacing the periodicity of the SIGRID is in the range of the pixel frequency of modern flat panel detectors. In combination with the high precision and reproducibility of the pattern, moiré-structures can be

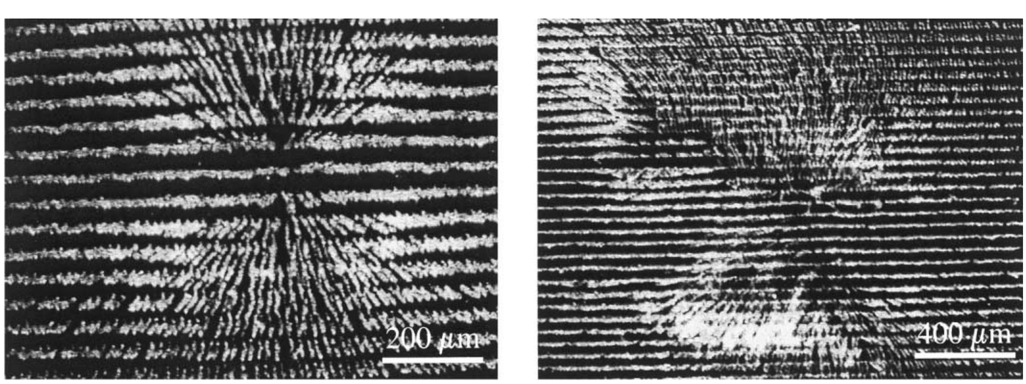

Fig. 8. Optical micrograph of the X-ray image shown in Fig. 7(b). Due to mechanical stress between silicon and epoxy resin the lead pillars are locally distorted which leads to shadowing effects.

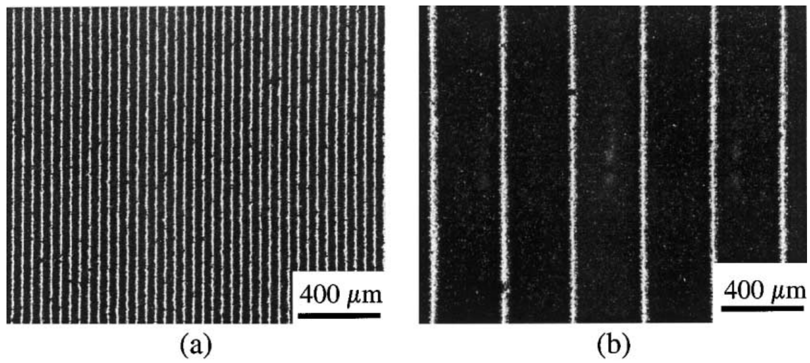

Fig. 9. Optical micrograph of the X-ray images of (a) the new SIGRID and (b) a conventional grid. The spacing between the lead lines is significantly reduced using the new technology.

avoided which makes the new grids favorable for the use in electronic imaging systems. To circumvent the above-mentioned problems processing with a lower thermal budget as well as the use of different resins are currently under investigation.

4. Conclusions

A MEMS based fabrication process for anti-scatter grid is presented which enables us to produce grids of an unequaled narrow spacing of absorbing elements. Preliminary results show that the performance of these grids compares well with conventional anti-scatter grids. The homogeneity of the new grids, however, has to be improved for application in X-ray imaging systems.

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Biographies

V. Lehmann received his diploma degree in electrotechnical engineering in 1983 from the Technical University of Aachen and his PhD in physics in 1988 from the University of Erlangen. In 1989 he received a Feodor-Lynen-Stipend of the Alexander von Humboldt Foundation and spent 1 year as a post-doc at Duke University in Durham, NC, working on wafer bonding and quantum size effects in porous silicon. He then joined the Corporate R&D Department of Siemens, Munich, working in the field of semiconductor process development with emphasis on electrochemical techniques. Presently he is project manager at Corporate Research of Infineon Technologies in Munich.

S. Rönnebeck was born in the Federal Republic of Germany in 1971. She received her diploma degree in mineralogy in March 1998 from the University of Kiel. Her diploma work dealt with the orientation dependence of macropore growth in n-type silicon. Since April 1998 she has been working on her PhD in a cooperation project between the group of Professor Dr H. Föll of the University of Kiel and the Corporate Research Department of Infineon Technologies in Munich. Her main research activities are applications of macroporous silicon for MEMS.