IMAGING OF MICRO- AND NANOSTRUCTURES WITH X-RAY TECHNIQUES: APPLICATIONS IN MICROELECTRONICS AND IN MICRO-SYSTEM TECHNOLOGY

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Abstract: Computed laminography with synchrotron radiation is developed and carried out for three-dimensional (3d) imaging of flat, laterally extended objects with high spatial resolution. Particular experimental conditions of a stationary synchrotron have been taken into account by a scanning geometry different from that employed with conventionally moveable laboratory x-ray sources. Depending on the mechanical precision of the employed sample manipulation system, high spatial resolution down to the of scale one micrometre can be attained nondestructively also for objects of large lateral size. Furthermore, the parallel-beam geometry enables easy use of monochromatic radiation for optimising contrast and reducing imaging artefacts. The feasibility of the method is demonstrated by the application to the inspection of solder joints in a flip-chip bonded device which shows the potential for quality assurance in microsystem devices.

Introduction:

The development and production of new materials and their application in components in various branches of microelectronics and microsystem technology require information on their structural perfection. Of crucial importance are especially structural properties and their relations to technological steps involved with their production. Moreover, the investigation of structure-property relationships for the components, starting from semiconductor substrate over layers and lateral structures up to the final component, *e.g.* the completed laser or integrated circuit, and beyond to the entire device, *e.g.* the finished PCB unit or hybrid circuit, is needed.

Beside laboratory methods, a reliable availability of experimental set-ups / stations at synchrotron radiation sources with their unique properties (high intensity and brilliance, good coherence properties of radiation at specimen) opens up advanced possibilities for nondestructive material characterization and for nondestructive testing (NDT) of components of applied and industrial research labs. The talk gives an overview illustrating synchrotron-radiation inspection and defect analysis in this context by results from microelectronics and microsystem technology, such as ultra-thin silicon for *smart wafers*, macrodefects in *GaAs*, dislocation density mapping in *semiconductor compound wafers*, growth and quality of *GaN-ELO structures* on sapphire and SiC, elastic strain in *semiconductor nanostructures*, *metallization layers* – stress migration in copper conducting lines, *lasers* – mechanical deformation fields in high-power laser bars, *flip-chip technology* – inspection of solder bumps in sensor arrays and pixel detectors, *microfluidics* – hydrodynamical permeability of micro filters, *MOEMS (micro-opto-electro-mechanical structures)* – stress in micro-mirror arrays. Different synchrotron imaging techniques of absorption-, phase- and diffraction contrast, such as holo-tomography, μ-diffraction, rocking-curve imaging and reciprocal space imaging are employed.

In the present paper, results of computed laminography are reported, which has been developed and implemented with synchrotron radiation for the first time and can be considered as a successful extension of three-dimensional (3d) synchrotron imaging to flat, laterally extended devices such as microelectronic circuit boards.

Today, x-ray computed tomography (CT) is one of the principal methods for volume imaging in medical diagnostics and quality assurance. CT has been developed during the 1960s/70s, for cross-sectional imaging in medical applications [1,2] and became in the 1980s also widely applied to NDT of materials and devices. With the installation of x-ray imaging set-ups at synchrotron-radiation (SR) sources, highest spatial resolutions down to the submicrometre scale could be reached [3] in radiographic images and weakly contrasted materials be distinguished [4,5,6] by phase-contrast imaging. Despite of the great success of CT in general, the CT inspection of flat, laterally extended objects with a high spatial resolution in comparison to the object dimensions (for instance printed circuit boards equipped with integrated circuits) is rather problematic due to strong absorption in the directions parallel to the lateral elongation.

Another approach was followed by a method nowadays called *classical x-ray tomography*. Already before the development of CT, it had been used to image specific cross-sections of objects (or patients). An acquisition scan consists of synchronous movements of the x-ray source and detector with respect to the object and exposing the detector (film) during the scan. In this way the so-called focal plane (defined by the geometric trajectories of x-ray source, object and detector during the scan) could be investigated: object features on the focal plane are imaged sharply whereas features with growing distance from this plane are rendered increasingly blurred and contribute to a background intensity in the image. The principle was already proposed in 1932 by Ziedses des Plantes [7] for the acquisition of a few arbitrary slices by a single scan. To obtain large 3d images with a multitude of slices, however, a translational scanning of the object with respect to the focal plane has to be carried out. Nowadays, in combination with digital projection data and a computerised reconstruction step [8], the scanning can be avoided: this so-called digital tomosynthesis has analogy to CT with limited angle access. Due to the availability of fast two-dimensional (2d) digital detector systems and the tremendous increase of computing power it has recently found renewed interest in medical [8,9] and technical [10,11] applications where the method is also called computed laminography (CL).

In this paper the development and implementation of computed laminography with synchrotron radiation, in the following called SRCL, is reported. SRCL combines laminography principles with advantages of SR imaging, owing to the use of monochromatic radiation (due to high brightness of SR) and a high spatial resolution down to the scale of one micron provided by dedicated electronic detector systems. In the following the methodic and instrumental feasibilities are demonstrated by an application to the inspection of flip-chip interconnections. The method's potential for nondestructive testing of microsystem technology and devices is outlined by the obtained results.

Medical tomosynthesis and laboratory CL systems are usually designed to operate with a stationary patient / object and synchronously moving x-ray tube and detector units. In contrast to the mobile x-ray tube the stationarity of the synchrotron source has to be accounted for by a modified scanning geometry involving now fixed source and detector and a rotation of the object. As sketched in Fig. 1, for SRCL the rotation axis is inclined by an angle of $\theta<\pi/2$ with respect to the monochromatic x-ray beam (where the limiting case of $\theta=\pi/2$ would correspond to CT).

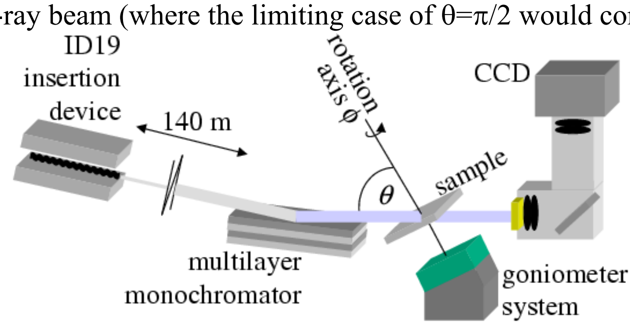

Figure 1: Sketch of the preliminary experimental set-up implemented at beamline ID19 of the ESRF.

From a coordinate system fixed to the sample and moving in the laboratory system, this scanning corresponds to synchronous movements of the source and detector on circular trajectories where the x rays follow a conic envelope during the scan.

In general for all laminography methods, sampling of the reciprocal sample space is not complete. In comparison to CT there exist unsampled regions which, quite generally, may lead to artefacts in the reconstructed images. Contrary to the laboratory (strongly divergent) cone-beam cases reported in [9,12], the approximations of a parallel beam and monochromatic radiation can be very well fulfilled in the case of SR imaging set-ups: in the developed implementation at ESRF beamline ID19 (cf. Fig. 1) the high source-to-sample distance of 145 m leads to a divergence of only approximately 0.02 mrad across the field of view of 2.8 mm of the employed CCD-based detector system. For instance, within the precision of one pixel size of 1.4 μm, a maximum sample depth of approximately 7 cm in direction of the x-ray beam is allowed in order to stay within parallel-beam conditions of one pixel precision. Moreover, the wavelength bandwidth provided by a multilayer monochromator is $\Delta\lambda/\lambda \approx 10^{-2}$ compared to $\Delta\lambda/\lambda \approx 1$ for the laboratory case.

The 3d reconstruction method is based on filtered back-projection where the back-projection geometry reflects the image acquisition geometry. After determining the modulation transfer function of the projection and back-projection processes, a filtering of the 2d projection data is designed to yield an approximate inversion of the back-projection process [9,13]. In general, due to the missing information in unsampled regions of 3d reciprocal sample space, exact inversion of the back-projection process is not possible which manifests in characteristic laminographic artefacts in the reconstructed image. Besides the gain of intensity and resolution of SRCL the monochromatic radiation and parallel-beam geometry reduces artefacts compared to laboratory white and cone-beam laminography.

Results: In order to demonstrate the potential of the method for NDT of microsystem technology we present results of a laminographic scan of a flip-chip bonded device. The flip-chip device was fixed by means of a cylindrical sample holder made from plexiglass on a rotation table. During the laminographic scan (using axis ϕ, see Fig. 1) over 360 degrees a total number of 900 projection radiographs was acquired at an x-ray energy of 35 keV. An axis inclination of $\theta=\pi/3$ was chosen.

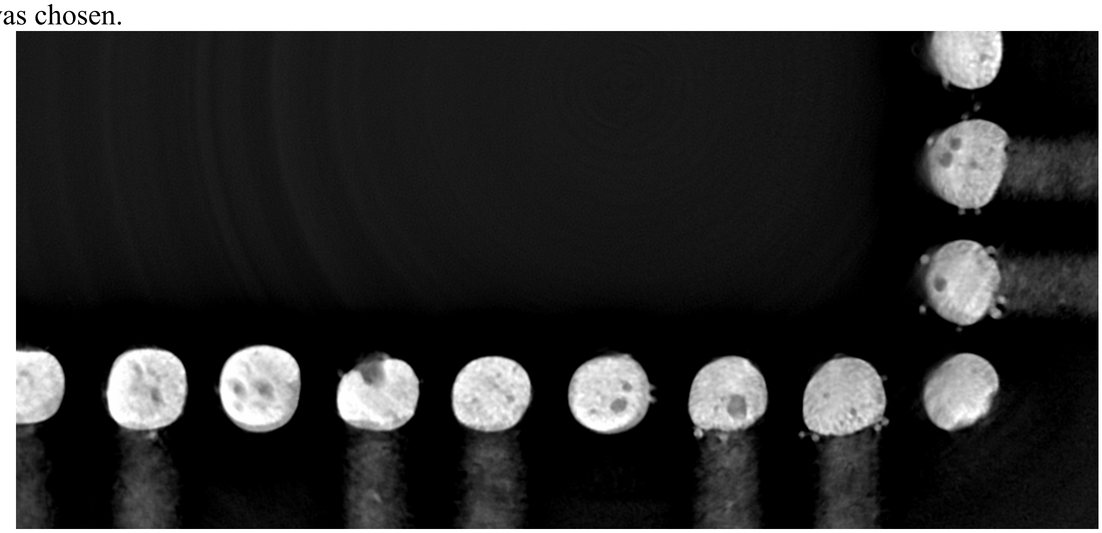

Figure 2: Cross-sectional slice through the reconstructed 3d data set of a flip-chip bonded device (top). A plane parallel to the printed circuit board is shown. 900 projections were acquired with an axis inclination of $\theta=\pi/3$ and at an x-ray energy of E= 35 keV. Voxel size is 1.4 μm, image width 1200 voxels.

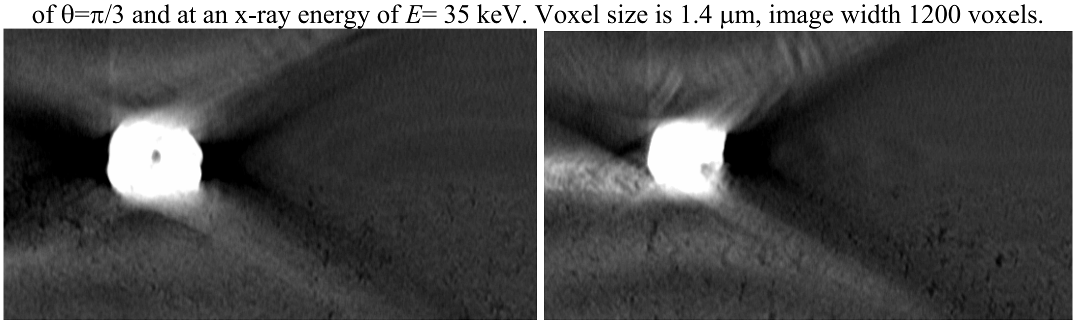

Figure 3: Cross-sectional slices perpendicular to the printed circuit board through the reconstructed 3d data set of a flip-chip bonded device. Two different solder joints are shown: with metallisation layer

stretching on the printed circuit board away from the electronics chip (left) and without (right). Voxel size is 1.4 μm, image widths 550 pixels.

Figs. 2 and 3 show reconstructed slices through solder joints of the device. The solder joints of approximately 80 to 100 μm diameter are hidden after the bonding process and thus are not accessible by visual inspection. SRCL allows us to identify deficiencies due to the bonding process. In addition to a high number of voids (see Fig. 2), solder splashes are also well discernable. Due to void sizes of up to 35 μm as determined by the reconstructed images, especially the voids entail a serious reliability hazard of the electronic circuit. Although the images of Fig. 3 show the presence of x-shaped artefacts — which are inherently connected to laminography due to missing information in reciprocal sample space — the electronics chip itself is slightly visible at the top, extending from the solder joints towards the right-hand side. Furthermore, inhomogeneities in the printed circuit board (pores) can be seen.

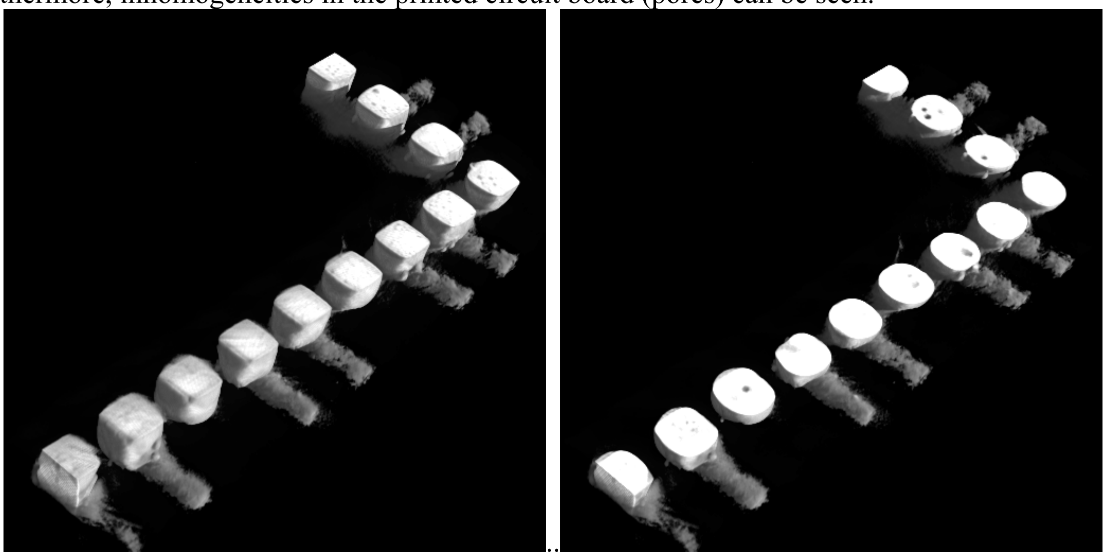

Figure 4: Renditions of the reconstructed 3d data set of the flip-chip device showing square-shaped metallisation layers joining the electronics chip (left) and where the top part is cropped to exhibit voids at the interior of the solder joints (right). Voxel size is 1.4 μm.

The high image contrast enables a 3d rendition of the data set after a simple segmentation step (by thresholding), as shown in Fig. 4. By cropping the upper part (towards the electronics chip) of the 3d data sets the interior of the solder joints can be inspected (right image). The copper metallisation on the printed circuit board is well visible by the stripes emerging from the solder joints. The image on the left-hand side points out the square-shaped metallisation layers on top of the solder joints deposited onto the chip surface.

Conclusions: The reported simulated and experimental results demonstrate the feasibility of synchrotron-radiation computed laminography. We implemented a set-up for a data acquisition geometry adapted to the stationary synchrotron source and reflecting the parallel-beam conditions. The obtained imaging quality highlights the potential of the method. It can be applied for nondestructive testing of flat, laterally extended objects such as electronic components or flat samples of microstructured materials.

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References:

[1] A. M. Cormack. Representation of a function by its line integrals with some radiological applications. *J. Appl. Phys.*, 34(9): 2722–2727, 1963.

[2] G. M. Hounsfield. *A method and apparatus for examination of a body by radiation such as X or Gamma*. Patent office, Pat. Spec. 1283915, London, 1972.

[3] U. Neuhäusler, G. Schneider, W. Ludwig, M.A. Meyer, E. Zschech, and D. Hambach. X-ray microscopy in Zernike phase contrast mode at 4 keV photon energy with 60 nm resolution. *J. Phys. D: Appl. Phys.*, 36: A79–A82, 2003.

[4] P. Cloetens, M. Pateyron-Salomé, J. Y. Buffière, G. Peix, J. Baruchel, F. Peyrin, and M. Schlenker. Observation of microstructure and damage in materials by phase sensitive radiography and tomography. *J. Appl. Phys.*, 81: 5878–5885, 1997.

[5] P. Cloetens, W. Ludwig, J. Baruchel, D. van Dyck, J. van Landuyt, J.P. Guigay, and M. Schlenker. Holotomography: Quantitative phase tomography using coherent synchrotron radiation. *Appl. Phys. Lett.*, 75: 2912, 1999.

[6] T. E. Gureyev, C. Raven, A. Snigirev, I. Snigireva, and S. W. Wilkins. Hard X-ray quantitative non-interferometric phase-contrast microscopy. *J. Phys. D*, 32: 563–567, 1999.

[7] B. G. Ziedses des Plantes. Eine neue Methode zur Differenzierung in der Röntgenographie (Planigraphie). *Acta Radiol.*, 13: 182–192, 1932.

[8] J. T. Dobbins III and D. J. Godfrey. Digital x-ray tomosynthesis: current state of the art and clinical potential. *Med. Phys. Biol.*, 48: R65–R106, 2003.

[9] G. Lauritsch and W. H. Härer. A theoretical framework for filtered backprojection in tomosynthesis. In *Proceedings SPIE; Medical imaging: Image Processing*, volume 3338, pages 1127–1137, 1999.

[10] J. Zhou, M. Maisl, H. Reiter, and W. Arnold. Computed laminography for materials testing. *Appl. Phys. Lett.*, 68(24): 3500–3502, 1996.

[11] S. Gondrom, J. Zhou, M. Maisl, H. Reiter, M. Kröning, and W. Arnold. X-ray computed laminography: an approach of computed tomography for applications with limited acces. *Nuclear Engineering and Design*, 190: 141–147, 1999.

[12] G. M. Stevens, R. Fahrig, and N. J. Pelc. Filtered backprojection for modifying the impulse response of circular tomosynthesis. *Med. Phys.*, 28: 372–380, 2001.

[13] A. K. Louis. Filter construction for circular tomosynthesis. *Private communication*.