Microsystem and Microelectronic Devices Investigated by Synchrotron-Radiation Imaging Techniques

Lukas HELFEN, Anton MYAGOTIN, Tilo BAUMBACH, Institut für Synchrotronstrahlung (ISS/ANKA), Forschungszentrum Karlsruhe, Germany
Marco DIMICHIEL, Lukas HELFEN, European Synchrotron Radiation Facility, Grenoble, France
Michael KRÖNING, Fraunhofer Institute for Nondestructive Testing (IZFP), Dresden, Germany
Tilo BAUMBACH, University of Karlsruhe, Germany

Abstract. Due to increasing packing density and ongoing miniaturization there is a growing need for non-destructive quality assurance of devices in microsystem technology, especially for techniques providing high spatial resolution. The tendency towards short electrical interconnections often results in burried structures which cannot be verified visually. In laboratories, various x-ray techniques are routinely applied to provide non-destructive insight into materials and devices. Successful application to microsystem devices is sometimes restricted, however, for instance due to limited spatial resolution and/or intensity of laboratory x-ray imaging setups. X-ray imaging using synchrotron radiation allows us to overcome a number of limitations. This paper introduces principles of both laboratory and synchrotron methods and shows their applications to imaging of microelectronic devices. Typical tasks of quality inspection usually accompanying the microsystem development cycle are demonstrated by examples of various fields of application.
High-resolution and phase-contrast radiography is used to detect delaminations between substrates and glob tops encapsulating wire-bonded devices. By three-dimensional (3d) imaging techniques as computed tomography (CT) we are able to image objects three-dimensionally with a spatial resolution down to the sub-micrometre scale. Recently, synchrotron-radiation computed laminography (SRCL) has been implemented to image three-dimensionally flat and laterally extended objects with high spatial resolution. Examples of flip-chip bonded and wire-bonded devices highlight the potential of SRCL in typical microsystem applications like the detection of µm-sized voids within flip-chip solder bumps along with their 3d positions in the bump. Moreover, as demonstrated by the study of two-dimensional hybrid x-ray sensor arrays with a high number of flip-chip interconnections, diffraction imaging methods have been developed and applied to investigate lattice deformations due to stress in (mono-)crystalline materials.

Introduction

In microelectronics and microsystem technology, the development and production of new materials and their application in components require information on their structural perfection. Structural properties and their relations to technological steps involved with microsystem production are of particular interest. The investigation of structure-property relationships for components, starting from semiconductor substrates over layers and lateral

structures up to the final component, *e.g.* the finished printed circuit board, is an important objective.
Complementing established laboratory methods, the exploitation of synchrotron radiation sources with its unique properties (high intensity and brilliance, good coherence properties of radiation at specimen) opens up new possibilities for advanced nondestructive material characterization and nondestructive testing (NDT) of components for publicly financed and industrial research laboratories. The talk gives an overview illustrating synchrotron-radiation inspection and defect analysis by selected results from microelectronics and microsystem technology, such as macrodefects in GaAs, elastic strain in semiconductor sensor layers, metallization layers and flip-chip interconnection technology. Different synchrotron imaging techniques exploiting absorption-, phase- and diffraction contrast, such as holo-tomography, laminography, full-field µ-diffraction imaging, rocking-curve imaging and reciprocal space imaging are employed.
In the present paper, results of computed laminography (CL) are reported, which has been developed [1] and applied [1,2] with synchrotron radiation (SR) for three-dimensional (3d) imaging of flat, laterally extended devices such as microelectronic circuit boards.

Experimental method

For local high-resolution three-dimensional imaging of laterally extended objects, synchrotron-radiation computed laminography (SRCL) was developed at the ESRF beamline ID19 in collaboration between ANKA/ISS (Forschungszentrum Karlsruhe, Germany), University of Karlsruhe and the german Fraunhofer association.
It consists in the acquisition of projection data sets of the object [1] under rotation around an axis which is inclined by a defined angle θ with respect to the incident x-ray beam, see Fig. 1. Subsequent computerised reconstruction allows a 3d image to be calculated from the projection radiographs, revealing the microstructure of the object. The experimental set-up is compared in Fig. 1 to the one usually employed for computed tomography (CT) at synchrotron-radiation imaging beamlines. The scanning geometry of CT with an axis inclination angle θ=90º can be considered as a special case of CL. For non-local CT [3,4], however, the object has to stay during rotation in the lateral cross-section of the beam (and the field of view of the 2d detector system) while in the case of SRCL the flat sample can significantly exceed the lateral cross-section of the beam. This allows high-resolution imaging of regions of interest in laterally large samples.

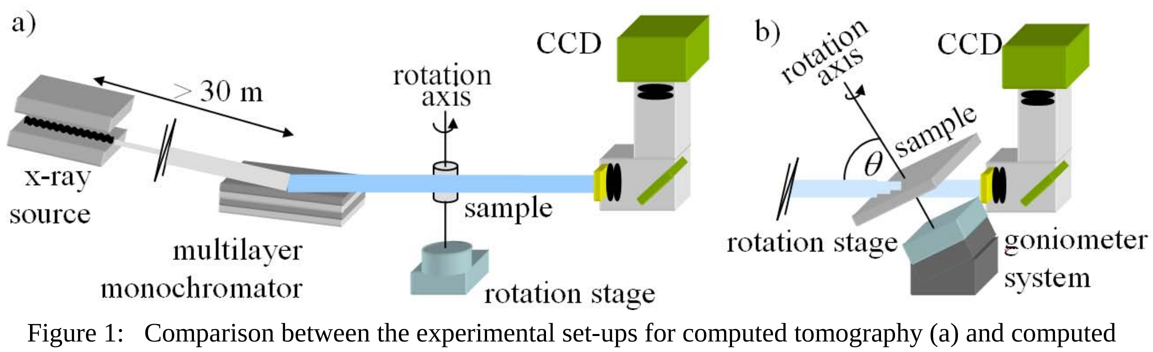

Figure 1: Comparison between the experimental set-ups for computed tomography (a) and computed laminography (b), as implemented at beamline ID19 of the ESRF.

In non-destructive applications where it is not admissible to cut out the interesting region as needed by CT, the potential of SRCL for high-resolution imaging has been demonstrated. In particular, electronic circuitry has been investigated both with monochromatic [1,2] as well as with white [2] synchrotron radiation, providing detailed information concerning interconnection technology. In comparison to similar laboratory methods, SRCL benefits from the availability of synchrotron radiation by its specific qualities, as *e.g.* high photon flux, low angular divergence and high partial coherence [5-7] in combination with high flux.

Results

SRCL has been applied to non-destructive imaging of a variety of flat, laterally extended objects with high spatial resolution. A selection of examples demonstrating its potential for microelectronic inspection will be presented in the following.

In Fig. 1, a 3d rendition of the bonding wires of a wire-bonded device is shown. Encapsulated in a glob top, the wires are not accessible by traditional visual inspection methods. The reconstructed 3d SRCL data set features both the wires and the metallisations used for bonding to the IC. This enables one to attribute device failures to microstructural problems, *e.g.* as arising by the bonding and/or glob-top encapsulation processes.

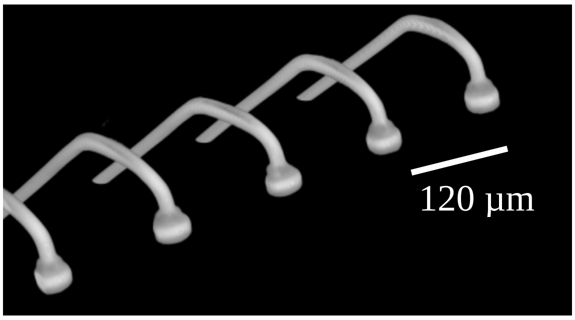

Fig. 2. 3D rendition of Au bonding wires of an IC encapsulated in a glob top against mechanical stresses. Voxel size is 1.6 µm, x-ray energy range approx. 40 to 60 keV.

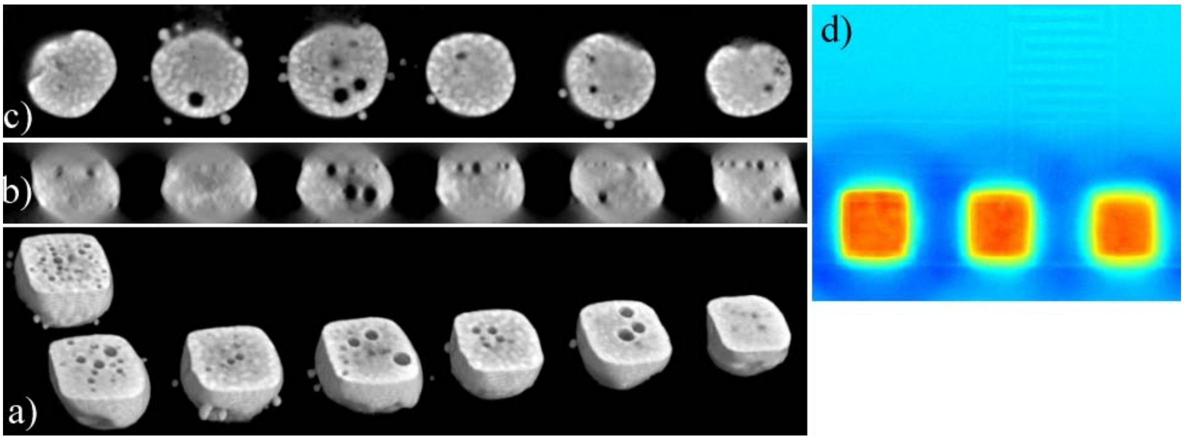

Fig. 3. SRCL inspection of a flip-chip bonded device: 3D rendition of some bump bonds at a device corner (a), two mutually perpendicular slices, perpendicular (b) and parallel (c) to the device surface. The coloured image (d) features a detail of metallisation layers on the hidden surface of the IC. Voxel size is 1.6 µm, x-ray energy range approx. 40 to 60 keV.

Fig. 2 shows the example of an SRCL inspection of a flip-chip bonded device. After bump bonding, the flip-chip solder joints are not accessible by visual inspection. The images show a 3D rendition (a) of bump bonds cut open by a plane. Voids in the bump bonds are clearly visible. Such voids affect the long-term reliability of the device when it is exposed to heating/cooling cycles, *e.g.* due to device operation. Images (b) to (d) are reconstructed cross-sectional slices showing a number of large voids and smaller voids, the latter predominantly at the interface to the IC's metallization layers (top part in b). The Pb-rich phase of the solder is well visible in slice (c), furthermore solder splashes near the bump bonds (small satellite spots). Slice (d) highlights a detail of the metallisations and conduction lines on the IC surface.

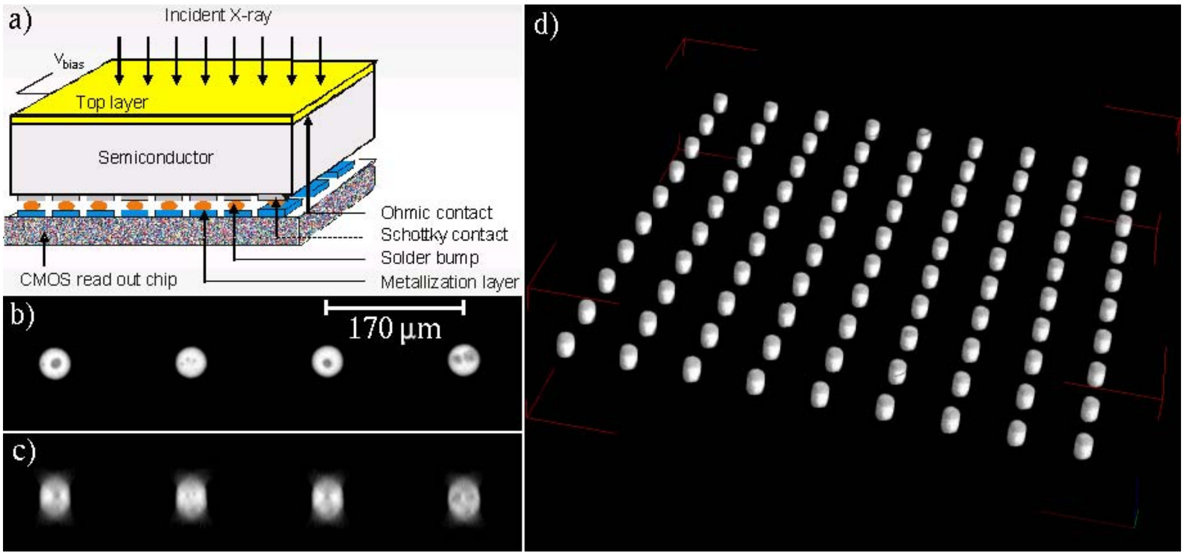

Fig. 4. SRCL inspection of a hybride detector array with a GaAs semiconductor sensor layer: sketch of the device (a), two mutually perpendicular slices, parallel (b) and perpendicular (c) to the device surface, and a 3D rendition (d) of the centre of the 2d array of bump bonds. Voxel size is 1.6 µm, x-ray energy range approx. 40 to 60 keV.

In Fig. 3, results of an SRCL inspection of a flip-chip bonded GaAs hybrid detector system are found. Due to the use of white beam, the projection data set containing 1800 radiographs were acquired in approximately 5 minutes scan duration. The 2d array of solder bumps, see scheme (a), is rendered three-dimensionally in (d). In this particular case, the bump bonds measure approximately 30 µm in diameter. Although the spatial arrangement and bump sizes are rather uniform, voids are present in the solder joints, see the two mutually perpendicular slices in (b) and (c).

Summary

SRCL provides a unique tool for non-destructive imaging of flat, laterally extended objects with spatial resolutions presently down to the µm scale. A dedicated set-up is scheduled to be installed in July 2006 which is designed to allow inspection scans with sub-µm precision.
One major application field aimed at is research and development in microsystem technology. For validation of production technologies and as a tool accompanying the device development cycle, SRCL could significantly contribute to understand the relationship between structural insufficiencies of devices and possible technological problems.

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References

[1] L. Helfen, T. Baumbach, P. Mikulík, D. Kiel, P. Pernot, P. Cloetens and J. Baruchel, *Appl. Phys. Lett.* **86**, 071915 (2005).

[2] L. Helfen, A. Myagotin, P. Pernot, M. DiMichiel, P. Mikulík, A. Berthold, T. Baumbach: „Investigation of hybride pixel detector arrays by synchrotron-radiation imaging“, *Nucl. Instr. Meth. A*, **in press**, (2006)

[3] A. M. Cormack. *J. Appl. Phys.*, 34(9): 2722–2727, 1963.

[4] 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.

[5] P. Cloetens, M. Pateyron-Salomé, J. Y. Buffière, G. Peix, J. Baruchel, F. Peyrin, and M. Schlenker. *J. Appl. Phys.*, 81: 5878–5885, 1997.

[6] P. Cloetens, W. Ludwig, J. Baruchel, D. van Dyck, J. van Landuyt, J.P. Guigay, and M. Schlenker. *Appl. Phys. Lett.*, 75: 2912, 1999.

[7] T. E. Gureyev, C. Raven, A. Snigirev, I. Snigireva, and S. W. Wilkins. *J. Phys. D*, 32: 563–567, 1999.