Application of the CrossBeam® Technology to TEM sample preparation and Nanolithography

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ABSTRACT

The use of focused ion beam (FIB) systems, including lithographic applications, has increased to a higher level in recent years [1]. The imaging, milling and deposition capabilities of the FIB makes it the ideal instrument for site-specific failure analysis, TEM specimen preparation and nano-machining. Also well known is the unique ion channeling contrast mechanism of the FIB induced secondary electron image, allowing selective imaging of polycrystalline and poly-phase microstructures. But, when viewed as evolving platform these stand-alone systems also represent an amalgamation of a basic process tool, an advanced analytical tool and a functional nanomanipulation system. This versatile tool suite is providing access to capabilities previously reserved for researchers with a full complement of semiconductor process equipment. Thus, this instrument provides unique capabilities for advanced materials research at the nano-scale, with application in MEMS prototyping, electronic and photonic nano-device prototyping, and studies of multifunctional materials.

INTRODUCTION

The standard FIB cross sectioning is basically a blind process. The sample surface is imaged with the FIB before cutting to determine the area of interest. Then the sample is milled and polished with predefined milling patterns. Without the possibility of simultaneous monitoring of the milling process the area of interest is easily destroyed. The capability of CrossBeam® technology to image the sample in real time at high resolution during the ion milling process using a field emission e-beam enables the operator to perform extremely accurate site-specific cross sections. The milling and polishing process can be stopped exactly at the detail of interest e.g. in the very centre of a certain transistor in a semiconductor device. In TEM sample preparation the real time SEM imaging allows for very tight control of the sample thickness/transparency and the danger of destroying the fine lamella is reduced to a minimum. The FIB lift-out technique allows thin membranes to be extracted from bulk material, which saves sample pre-thinning time and is very successful in the preparation of site-specific cross sections and planar samples. To a large extent TEM sample preparation can be automated by using scripts and macros. However, the best compromise concerning time and accuracy is achieved if different samples are pre-thinned automatically overnight to a thickness of about 1µm and then polished manually under high resolution SEM observation. For the final investigation of the TEM lamellae energy filtered analysis allows for optimum image contrast even for thicker samples or heavy material structures in back-end analysis since the chromatic blur from inelastically scattered electrons can be eliminated. By selecting appropriate energy loss windows element specific contrast enhancement and quantitative determination of 2D composition distributions can be achieved. Moreover, using the small probe size of current FEG instruments, spectroscopic analysis in STEM and nanoprobe modes can reveal composition and interface properties on the sub-nanometre scale.

TEM SAMPLE PREPARATION

Conventional TEM preparation techniques

Conventional preparation techniques for cross sectional TEM samples are a combination of mechanical grinding polishing and ion milling (Fig. 1). These techniques suffer from the fact that they are very time consuming and that it is extremely difficult to do site specific cross sections. Conventional ion-milling techniques for TEM specimen preparation are essentially blind. Thus, it is left to chance whether the specimen detail of interest is suitable for TEM-imaging (many specimen areas are too thick). Even if subsequent ion milling of TEM specimens is possible in external ion milling stages it is a tedious and mostly uncontrolled procedure. Because continuous high-resolution control of the ion milling process is not possible, the specimen areas of interest may easily be destroyed.

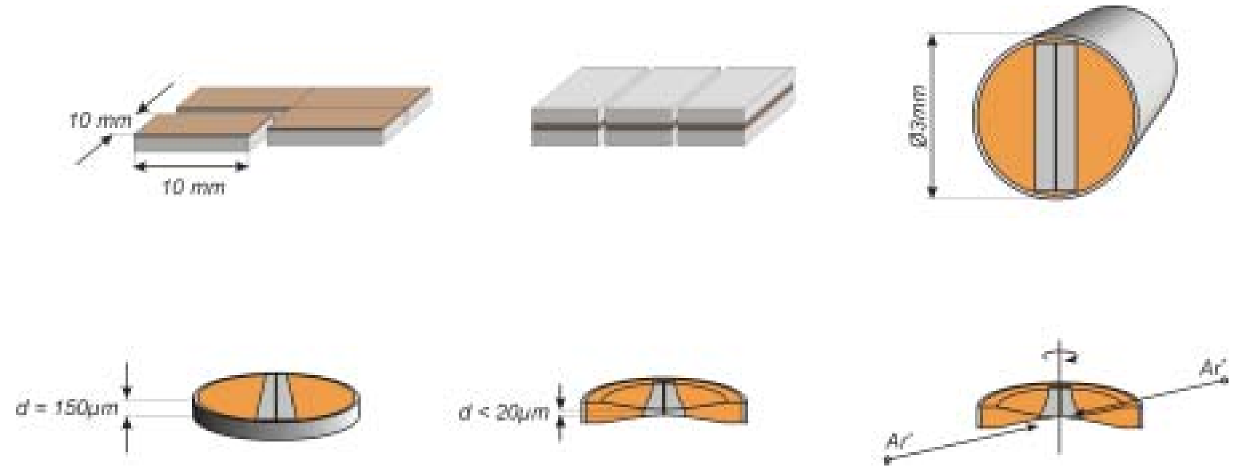


Fig. 1: Steps during the cross sectional TEM preparation using dicing, grinding, dimpling polishing and broad ion milling

TEM Sample Preparation using FIB

An advantage in the TEM sample preparation regarding time consumption and the possibility of being site specific the introduction of the focussed ion beam technique into TEM sample preparation was a big advantage. The sample surface is imaged with the FIB before cutting to determine the area of interest. Then the sample is milled and polished with predefined milling patterns. In the final step the sample can be cut out of the substrate and transferred to a TEM grid. But as only the sample surface imaged even the standard FIB cross sectioning is basically a blind process Without the possibility of simultaneous high resolution monitoring of the milling process the area of interest is easily destroyed.

TEM Sample Preparation using the CrossBeam® technique

The solution for the problems described above is the combination of a FIB system with a high-resolution field emission SEM to allow high-resolution real time imaging of the ion milling process. In this case a detail of interest cannot be missed or destroyed (Fig.2). Another advantage of this approach is the charge compensation on insulating materials as ceramics, oxides and resist material.

2.1 **2.2** **2.3** **2.4**

Fig. **2**: Steps during TEM sample preparation using the CrossBeam®: The sample surface is visible during the whole process
2.1 Sample definition and rough milling 2.2 Fine milling and final polish 2.3 Cut 2.4 Lift out

EXPERIMENTAL

To do the sample work the LEO1540XB CrossBeam® Workstation was used. The System combines the high resolution GEMINI field emission column with the CANION 31+ FIB column. The tool was equipped with a five-channel gas injection system for deposition and enhanced etching and with an annular STEM detector to perform bright field and dark field STEM imaging at sub nanometre resolution.

IMAGING MODES

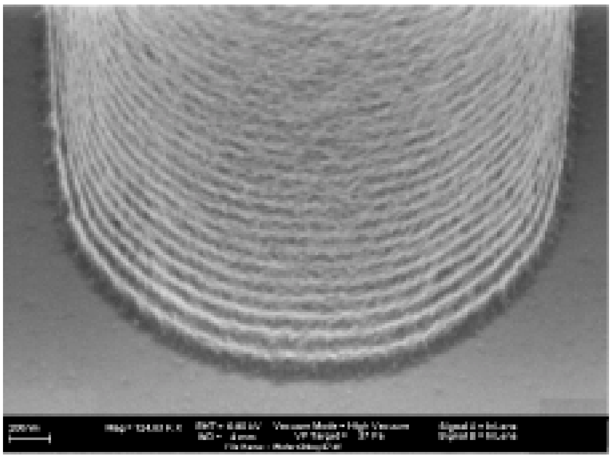
The CrossBeam® system can operate at three different imaging modes. By blanking the ion beam and only using the electron beam for imaging the system operates as high-resolution field emission SEM. The second imaging mode uses the ion beam while the electron beam is blanked. The FIB imaging mode is used for grain analysis, voltage contrast imaging and defining of milling areas. The last imaging mode is the so-called CrossBeam® operation mode: Both beams are turned on and while the ion beam is milling a defined area, the SEM is used to image the milling process at high resolution in real time. This enables the operator to control the milling process on a nanometre scale and to perform extremely accurate cross sections and device modifications.

SEM imaging

If the system is used as a high resolution SEM only the ion beam is blanked and the SE-signal is synchronized to the SEM scan. In this operational mode the system is used as a high resolution FE-SEM with no limitations (Fig. 3).

FIB imaging

If the system is used as a FIB only the SEM beam is blanked and the signal is synchronized to the FIB scan. This mode is used for channelling contrast imaging, voltage contrast imaging and for defining milling patterns on the sample surface.



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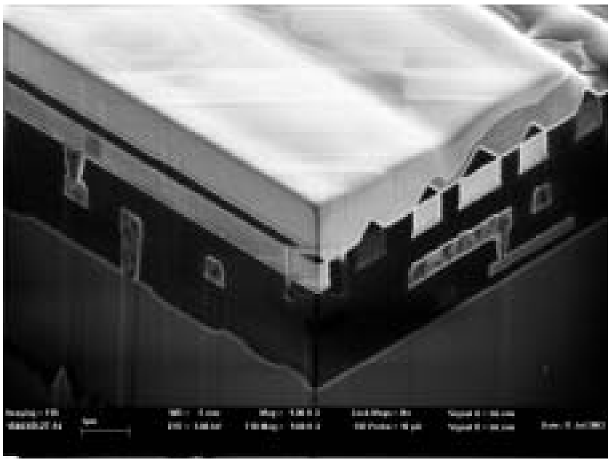

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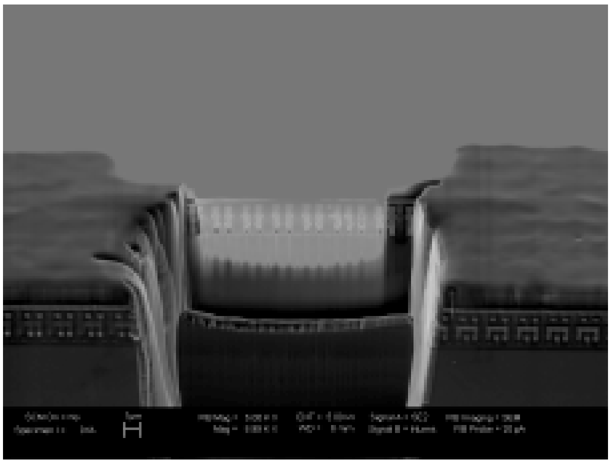
Fig. **3, 4**: High-resolution low voltage (800 V) SEM image of an uncoated photo resist structure on a silicon wafer (left) and FIB imaging: Channeling contrast and voltage contrast in a semiconductor sample.

CrossBeam® operation

To monitor the ion milling process in real time at high resolution in the SEM the CrossBeam® operation is used. Both beams are turned on and while the ion beam is milling a defined area, the SEM is used to image the milling process at high resolution in real time. This enables the operator to control the milling process on a nanometre scale and to perform extremely accurate cross sections (Fig. 4) and device modifications. It is possible to obtain clear live images even at higher ion beam currents above 2 nA.



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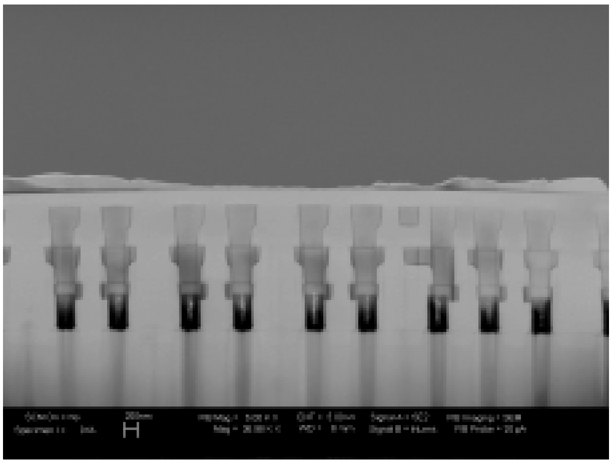

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Fig. **5, 6**: Live imaging of a TEM sample during ion milling. While the location of the sample can be monitored at high precision (the plugs are cut exactly in the center), the electron transparency can easily determined by the brighter contrast (note different brightness for different elements).

This mode also provides an easy way to compensate charging on non-conductive samples. The sample is irradiated by the positive ion beam and the negative electron beam at the same time. The result is an easy way of charge compensation on the sample surface.

Another very important benefit of this mode is the easy and direct control of the specimen thickness during ion milling. As the sample gets thinner the primary electrons start penetrating the sample and generate secondary electrons on the backside. These electrons can be detected by using the Everhart-Thornley detector, which is geometrically located behind the sample (Fig. 7). This signal gives direct information about the thickness of the sample: The thinner the sample, the brighter the image. To do exact measurements of the sample thickness the brightness of the signal can be calibrated for certain materials [2]. At the same time the sample surface can be imaged using the In-lens detector, which is geometrically located in front of the sample and collects mainly secondary electrons that are emitted from the sample surface (Fig. 7). By combining both signals during the ion milling in a split screen mode the complete information about the sample (location, surface detail and thickness) can be displayed at the same time (Fig. 8,9).

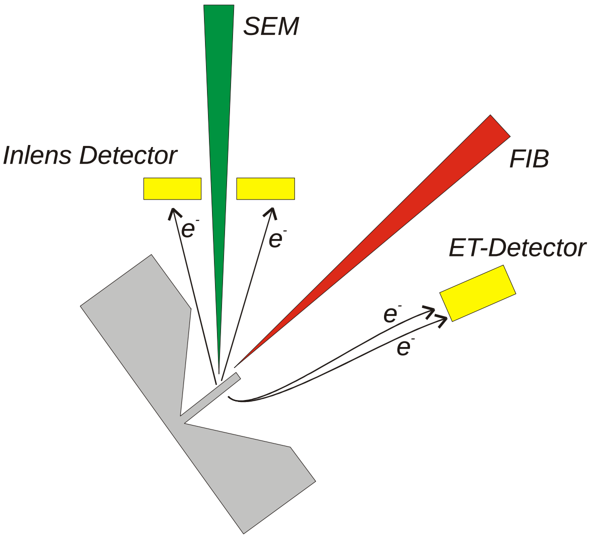
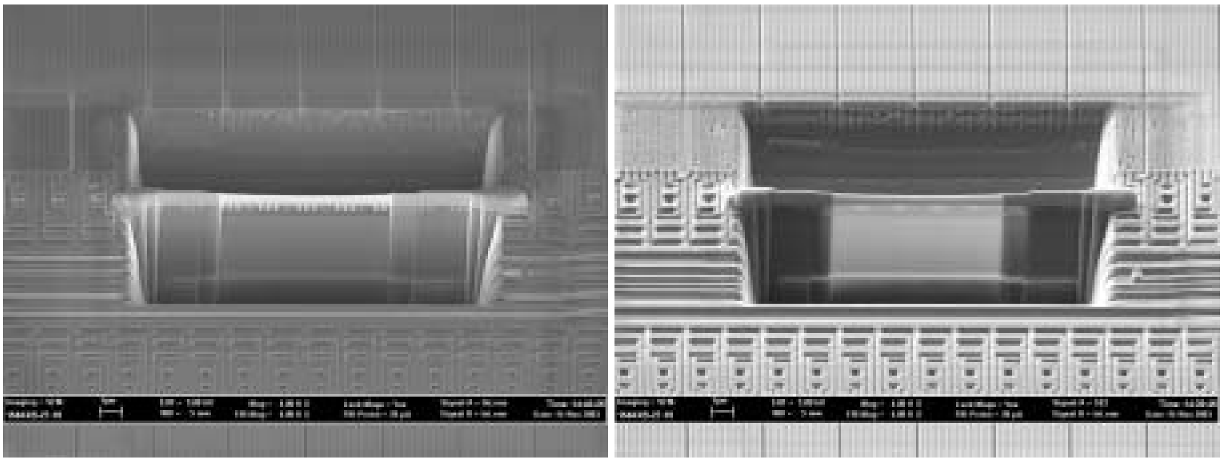


Fig **7**: Geometrical position of the sample and the detectors during ion milling in the CrossBeam®. The In-lens detector is located in front of the sample and records information about the sample surface. The ET (Everhart-Thonley) detectector is located behind the the sample and records SE that are emittet from the backside of the sample.

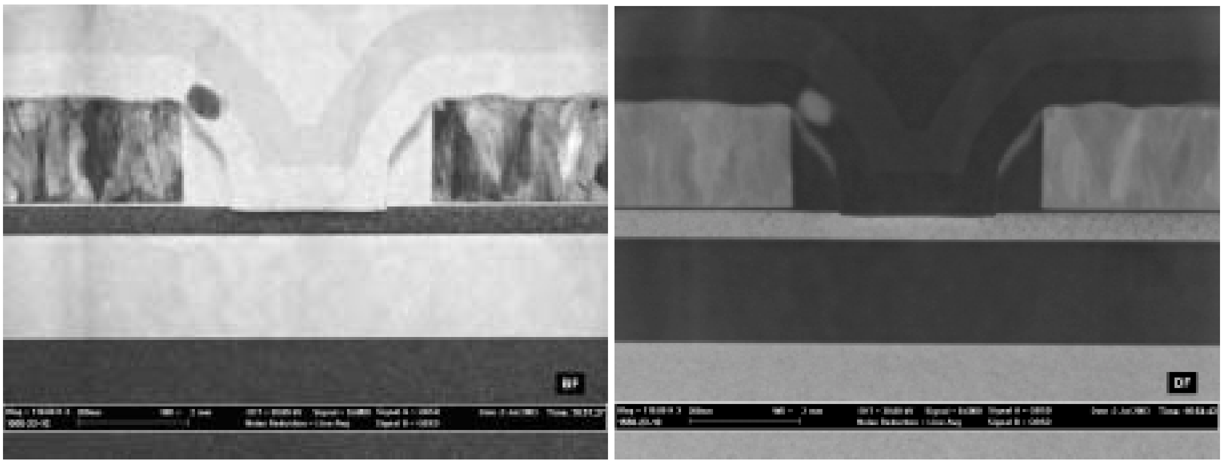


8 **9**

Fig. **8, 9**: Live imaging of semiconductor TEM sample during ion milling. While the In-lens detector on the left displays information about the sample surface the Everhart-Thornley detector signal on the right provides information about the transparency at the same time.

STEM imaging

The real time imaging enables for extremely accurate and site specific cross sections. Fig. 10,11 display an example of a sub µm defect in a semiconductor sample that could be located by using the live imaging possibilities of the CrossBeam®. The image was taken using the STEM mode of the CrossBeam® system.



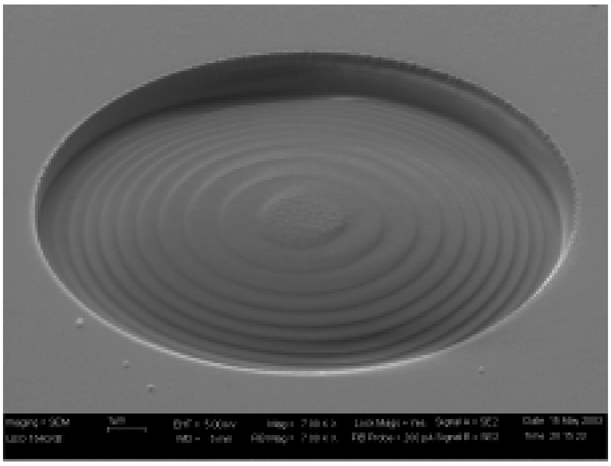
10 **11**

Fig. **10, 11**: 30 kV bright field (left) and dark field (right) STEM images of a semiconductor structure. A very small defect was exactly hit in the center.

Direct-write nanolithography

In terms of interesting lithographic applications, FIB enables direct write patterning of material systems that cannot be addressed through traditional semiconductor processing, such as the micro-lens machined into a glass fibre shown in Fig. 12. In this work we will discuss similar examples that highlight the unique opportunities made available through FIB direct write process, including patterning in ceramics and metals. In addition, we will provide examples of FIB patterning applied to prototype production of novel electronic and photonic structures, such as the photonic crystal devices shown in Fig 13.

Throughout this work we will also highlight the ability to image and capture the entire patterning process in real time at high resolution, a unique capability of the CrossBeam® tool. This additional capability translates into superior end point detection and process control, giving the operator full interactive control during the direct-write process.



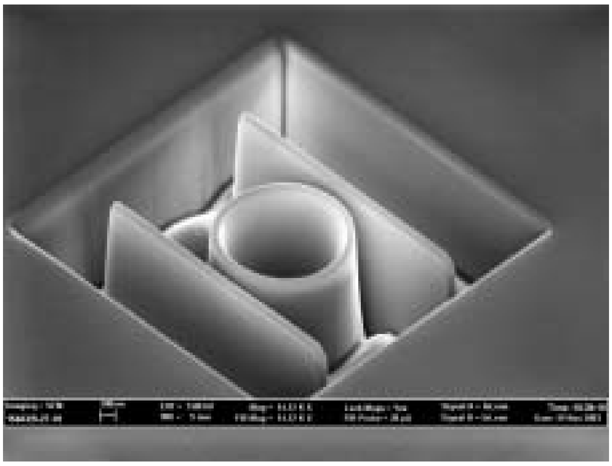


Fig. **12**: Micro machined micro-lenses in a glass fibre . The structure was produced using direct FIB writing under continuous SEM control. Sample courtesy of INFM, Trieste, Italy	Fig. **13**: Photonic crystal structure in GaAs. The patterning was done by using gas assisted etch to achieve high aspect ratios.

REFERENCES

[1] E. Weimer, J. P. Martin: “Development of a new ultra high performance scanning electron microscope”, 13th Int. Congr. on Electron Microscopy ICEM, Vol.1, pp. 67-68.

[2] G. Auvert, FIB Dual-Beam Sample Preparation for TEM observation, Microscopy and Microanalysis 2003, San Antonio, TX, August 3 – 7, 2003.