Mechanical Conversion for High-Throughput TEM Sample Preparation

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Abstract. This paper presents a novel method of direct mechanical conversion from lift-out sample to TEM sample holder. The lift-out sample is prepared in the FIB using the in-situ lift-out Total Release™ method. The mechanical conversion is conducted using a mechanical press and one of a variety of TEM coupons, including coupons for both top-side and back-side thinning. The press joins a probe tip point with attached TEM sample to the sample coupon and separates the complete assembly as a 3mm diameter TEM grid, compatible with commercially available TEM sample holder rods. This mechanical conversion process lends itself well to the high through-put requirements of in-line process control and to materials characterization labs where instrument utilization and sample security are critically important.

1. Introduction

In 1965, Gordon Moore forecast that the microprocessor industry would continually scale to smaller feature sizes and the number of transistors would double every 18 months. Scaling below the 100nm node, combined with the implementation of copper and low dielectric constant insulators to reduce the RC time delay, has produced the situation in which SEM inspection no longer offers suitable resolution to image key artifacts and structures. The transmission electron microscope (TEM), once considered more of a development tool, is now in the forefront for process control and failure analysis, especially for measurements such as the thickness of non-planar barrier and seed layers. The use of dual-beam focused ion beam (DB-FIB) microscopes has become the method of choice for site-specific TEM sample preparation. Originally, the DB-FIB was used as a final thinning step for mechanically prepared ribbons of semiconductor material adhered to modified TEM grids, known as the “H-Bar” method. More recently, the method for performing the entire TEM sample preparation process within the DB-FIB is known as "in-situ lift-out" and is based on the use of a chamber-mounted nanomanipulator and beam-induced material deposition [1-5]. The use of the DB-FIB offers advantages over conventional mechanical TEM sample preparation. The dual-beam FIB offers the ability to locate the lift-out site with SEM resolution and then use the ion beam to excise the sample without sacrificing the wafer, followed by thinning the extracted sample to the thickness required for TEM inspection. This is especially attractive for 300mm processing where the value of each wafer in the flow can exceed $100,000. The risk to the quality and reliability of the process wafer due to gallium contamination from the ion beam is considered manageable [6]. In-situ lift-out also enables the return of the mostly abandoned practice of including informative test die on product wafers.
2. TEM Sample Preparation by In-Situ Lift-Out

A method for high-throughput TEM sample preparation by in-situ lift-out in the FIB is described here [4-5]. The Total Release™ method can be simplified into three successive steps (see Figure 1). The first is the excision of the lift-out sample using FIB milling and extraction of the sample from its trench with two rapid ion milling steps, or “cuts”. The first cut is “U”-shaped and partially surrounds the target. The second is a straight cut that intersects the first cut beneath the target and produces a wedge-shaped sample. Then the probe is fixed to the released sample, typically with ion-beam metal deposition, and the sample is removed from the wafer by the nanomanipulator. The second step is the “holder-attach” step, during which the wedge is translated on the probe tip to the TEM sample holder (the lift-out grid). Then the sample is attached to the TEM holder (again, typically with ion beam-induced metal deposition) and later detached from the probe tip point using FIB milling. The third and final step is the thinning of the wedge into an electron-transparent thin section using FIB milling.

The use of a simple probe tip for lift-out in the FIB has throughput and efficiency advantages over alternative methods. For example, lift-out can also be accomplished by a method referred to as ex-situ lift-out, in which ion beam-thinned samples, still attached to the wafer, are removed from the FIB and then detached from the wafer with a statically charged glass needle. These samples are then permanently deposited onto the suspended areas on a polymer membrane-coated TEM grid. Ex-situ lift-out can be faster than the in-situ method, and it requires less time in the FIB. However, in-situ lift-out offers a much higher overall throughput through automation of the process within the FIB environment. In-situ lift-out also provides the ability to return the TEM sample to the FIB for additional thinning, better protection of the delicate sample, better thermal and electrical grounding of the sample in the TEM and cleaner samples.

![Fig.1. Typical steps of in-situ lift-out with the Total Release method: (1) first cut; (2) release cut; (3) tip attach; (4) extraction; (5) holder attach; and (6) tip separation.](image-url)
3. Mechanical Conversion

A significant portion of the preparation time is spent in transfer and attachment of the sample to the TEM grid (typically 30% to 60% of the total time). Experience with novice operators, shows their first lift-out is accomplished in about two hours. Of these two hours, sample handling accounts for approximately 17%, or 21 minutes; excising the sample takes up approximately 27%, or 32 minutes; lift-out requires approximately 13%, or 16 minutes; the grid attach step requires approximately 26%, or 31 minutes; and final thinning requires approximately 17%, or 20 minutes. Mechanical conversion of the lift-out sample directly to TEM sample holder eliminates the holder-attach step, and replaces this step with approximately 3-4 minutes of additional sample handling associated with releasing the probe tip with a sample attached to it to a cassette, taking this cassette outside the FIB, delivering it to the press location and completing the press operation. This time estimate is approximate and will depend on the operator and the type of DB-FIB microscope used.

This elimination of the grid attach step provides several key throughput and resource utilization advantages for in-line process control in addition to raw time savings (see Figures 2-5) [7]. For example, the semiconductor wafer can be returned to the process flow immediately after lift-out. Thinning of the sample can be performed immediately, or later in an off-line FIB. The use of the off-line FIB for final thinning reduces the load on the critical in-line (clean room) FIB and is well suited for an automated sample preparation procedure. This mechanical conversion process provides rapid, low cost and robust bonding of the probe tip point and the standard 3mm TEM holder. As more semiconductor products migrate to sub-100nm geometries, the need for low-cost, high-throughput and site-specific TEM sample preparation will increase in importance.

The process of mechanical conversion is conducted using a mechanical press (shown in Figure 2). This press can be located either inside the FIB or outside of the FIB, and for in-line operations, outside of the clean room. For high throughput applications, separating the mechanical conversion from the in-line 300mm FIB will reduce the time spent in this expensive asset and reduce the time before the wafer can be returned to the process flow. The press mechanically isolates the TEM sample holder from the TEM coupon and joins the probe tip point with an attached TEM sample to the sample holder. Being a mechanical procedure, this type of conversion is very reliable. It provides strong and robust bonding of the probe tip point and the TEM grid. Other advantages of the mechanical conversion include its low cost and speediness. A standard 3mm diameter TEM grid is produced which is compatible with any conventional TEM holder.

Fig.2. A schematic of the press for mechanical conversion, the TEM holder coupon and the probe tip with sample attached.

Fig.3. The finished 3mm TEM sample holder designed for top-side milling with one tip attached.

Coupons are available for both top-side and back-side thinning of the TEM sample. The first type is designed for milling the TEM sample from the top-side (surface of die) and the subsequent TEM sample remaining after conversion is shown in Figure 3. The second type is designed for back-side milling to avoid the “shower curtain” effect that may occur in top-side thinning due to reduced milling speed at patterned dense materials at the device surface [8].
The example of mechanical conversion performed by an operator is shown in Figures 4 and 5. The probe tip with a TEM sample attached to it is released into the cassette, located inside the FIB, and the cassette is transferred outside the FIB. In Figure 4, an operator transfers the FIB cassette with the lift-out sample to the mechanical conversion anvil. In Figure 5, the operator performs the process of mechanical conversion of the lift-out sample to the TEM sample using the mechanical press.

Fig. 4. Transfer of the FIB cassette with a lift-out sample to the mechanical conversion anvil.

Fig. 5. Mechanical conversion of the lift-out sample to TEM sample.

4. Conclusion.
A new method and apparatus for mechanical conversion of the in-situ lift-out sample on the probe tip to a TEM sample has been developed. This approach is particularly effective for high-throughput applications such as in-line process control, and maximizes the use of FIB resources in the process, where an in-line large-wafer dual-beam FIB is used to extract the lift-out samples, and an off-line small dual-beam FIB is used for final thinning of the TEM sample.

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