APPLICATION OF FOCUSED ION BEAM FOR FAILURE ANALYSIS

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Abstract: The focused ion beam (FIB) technique is an important tool for failure analysis studies on electronic devices. Examples are discussed of the identification by cross-section imaging of failure sites previously localized ex-situ by optical or emission microscopy or in-situ by means of voltage contrast in the FIB system. Ex-situ chemical analysis by Auger electron spectroscopy on FIB prepared cross-sections allows detailed interpretation of the FIB images.

Uporaba curka fokusiranih ionov pri analizi odpovedi

Ključne besede: naprave elektronske, analize odpovedi, FIB curek ionov fokusiran, polprevodniki, FIB tehnika curka ionov fokusiranega, upodabljanje površine

Izvleček: Curek fokusiranih ionov (FIB - Focused Ion Beam) je pomembna tehnika za analizo odpovedi elektronskih komponent. V prispevku obravnavamo primere prepoznavanja mest odpovedi na slikah presekov, katera so bila prvotno identificirana s pomočjo ex-situ tehnik, kot sta optična ali emisijska spektroskopija, oz. in-situ tehnike, kot je napetostni kontrast v FIB sistemu. Ex-situ kemična analiza s spektroskopijo Augerjevih elektronov na presekih vzorcev pripravljenih s FIB tehniko omogoča natančno analizo in tolmačenje FIB slik.

1. Introduction

The focused ion beam system is an indispensable technique for the semiconductor industry. Its major applications are: circuit modification by cutting metal lines and deposition of new metal tracks for optimizing the circuit design /1-3/; cross-section imaging for process development and control /2, 4/; failure analysis /5-7/ of devices by cross-section imaging through suspicious structures and voltage contrast to localize open contacts; preparation for in-situ or ex-situ chemical analysis; preparation of specimens for transmission electron microscopy /8, 9/; mask repair; milling and layer deposition for MEMS structures.

In this paper the technique is briefly introduced and a number of applications of the FIB technique for failure analysis are discussed.

2. The FIB technique

In the FIB system a focused 30-50 keV Ga^+ ion beam is rastered over the sample in a similar way as the electron beam in a scanning electron microscope (SEM). The secondary electrons or ions generated by the interaction of the ion beam with the material are collected synchronously with the rastering of the primary beam and are used to image the surface of the sample.

The contrast in the secondary electron FIB images /10, 11/ is different from the contrast in secondary electron SEM images. As the primary beam is positively charged, isolators will charge positively and will show a low secondary electron yield. Hence, they will be dark on the images. On the other hand, conducting materials will be bright if they are connected to the substrate holder of the system so that the current induced by the primary beam can flow away. If this is not the case, i.e. if the metal tracks are floating, they will also have a dark contrast. This allows the localization of failure sites by voltage contrast /12, 13/ as will be discussed in next section. An important image characteristic is also the channeling contrast in polycrystalline metal layers. In poly crystalline silicon this contrast is however not present due to the immediate amorphization of the top layer (~60 nm deep) of the silicon which suppresses the channeling of the ion beam. The border between conductive and non-conductive materials always shows a bright line, which is a result of the lateral field on the surface between both regions. The different contrast effects are illustrated on figure 1.

Except of the application for imaging, the high energy ion beam can also be used to remove the material locally by milling trenches in the material. This allows after tilting of the sample, the imaging of the cross-sectional structure of the device on the sidewall of these trenches. As the position of the trenches can be localized accurately from the top view image, very site-specific cross-section analysis is possible.

Another important application of the milling with the ion beam is the cutting of metal lines in prototype IC's to study possible design errors. Generally this is done in combination with the inlet of specific gases. This gas assisted etching (GAE) strongly reduces the redeposi-

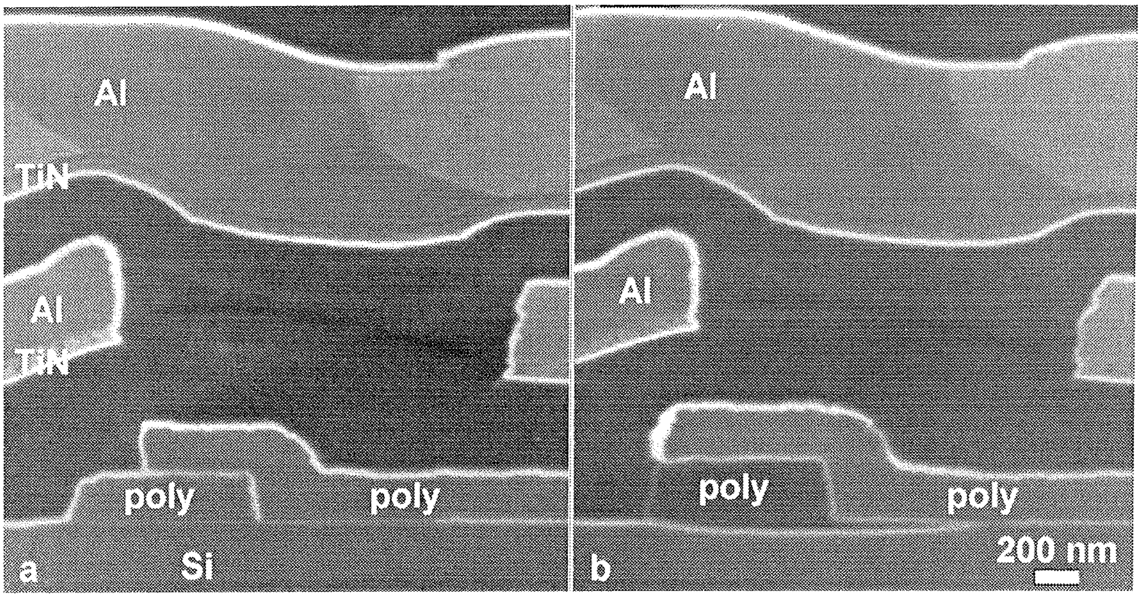

Fig. 1: *Cross-section FIB images through a HIMOS memory cell illustrating the different contrast mechanisms on the FIB images: the isolators are dark; the conductors (Al, TiN, Si) are bright; the Al shows channeling contrast; the poly-Si shows no channeling contrast; bright lines mark the border between the dielectrica and the conductors. This bright line also reveals the presence on a thin oxide between the poly lines and the silicon substrate and between the two poly lines. In image (b) a further slice of the device was milled away so that the poly-Si line is now on top of a thick field oxide and is therefore floating with respect to the substrate and now shows a dark contrast.*

tion of the removed material, results in an enhanced milling rate, and allows the selective removal of certain types of materials. E.g. Al is etched with I_2 or other halogen gases, passivation layers with XeF_2 and C-based materials with H_2O. Specific gases can also be used to deposit metal lines (Pt or W) or dielectrica (SiO_2). Only where the beam is rastered, the gas molecules are cracked and deposition occurs. The combination of deposition of new metal tracks and the cutting of metal lines allows the local rewiring of the metal interconnects in the devices.

The selective etching of dielectrica with the XeF_2 is also used for the local depassivation of devices for e-beam testing. Organic passivation layers (e.g. polyimide) can be removed very selectively with the H_2O milling (Fig.2).

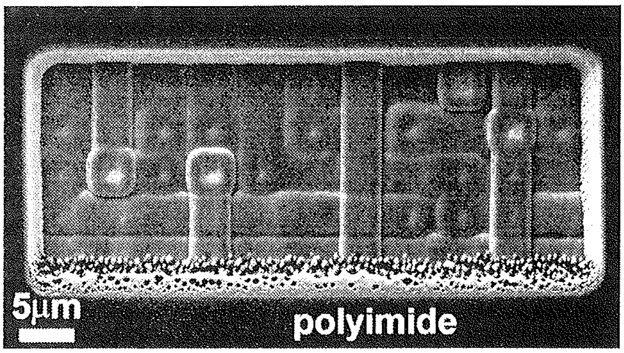

Fig. 2: *Selective removal of a window through a 7 µm thick polyimide passivation layer by application of gas assisted milling with the H_2O gas. Due to the high selectivity the milling stops at the nitride passivation layer on the device.*

3. Applications for failure analysis

The focused ion beam technique can be used to characterize the nature of failure sites in device structures. The localization of the defect sites can be done ex-situ by e.g. the liquid crystal method, optical microscopy or emission microscopy, or in-situ by means of voltage contrast.

3.1 Failures localized by optical microscopy

Figure 3 shows FIB cross-section images through poly-resistor structures. Fig. 3a illustrates a device before the electrical testing, showing the Al metal tracks, the W plugs and the polycrystalline silicon line. After electrical testing a dark spot could be seen by optical microscopy

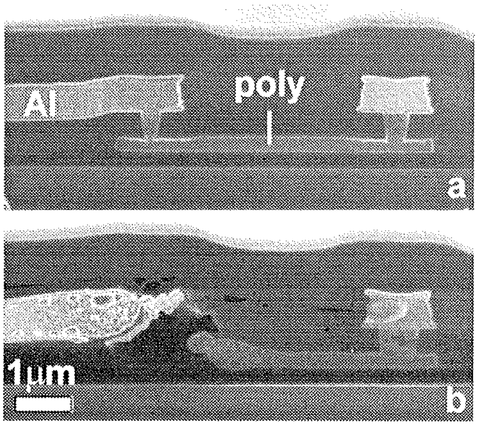

Fig. 3: *FIB cross-section images through an untested poly-resistor (a) and after electrical testing (b).*

through the passivation layer. Fig. 3b shows that the device structure is severely damaged by the testing: the Al and poly line have a sponge-like structure, a large void is formed at the position of the W plug which has totally disappeared, and also in the metal line on the right hand side a void is formed. The damage clearly indicates that a strong overheating occurred due to a too high current flowing through the device.

3.2 Failures localized by emission microscopy

Failure sites can be localized in devices by emission microscopy /14/. While electrically biasing the devices the local heating at failures will result in the emission of IR light. FIB cross-sectioning can subsequently be done at these positions to study the nature of the failure.

Fig. 4 shows an example where the defect could be seen already in the top view FIB image so that the exact localization of the defect in the FIB was very easy. The cross-section image (Fig. 4b) reveals a crater-like structure. The lower metal track is broken and shows a short with the upper metal line. Resist residues or a particle might have been on the origin of this defect.

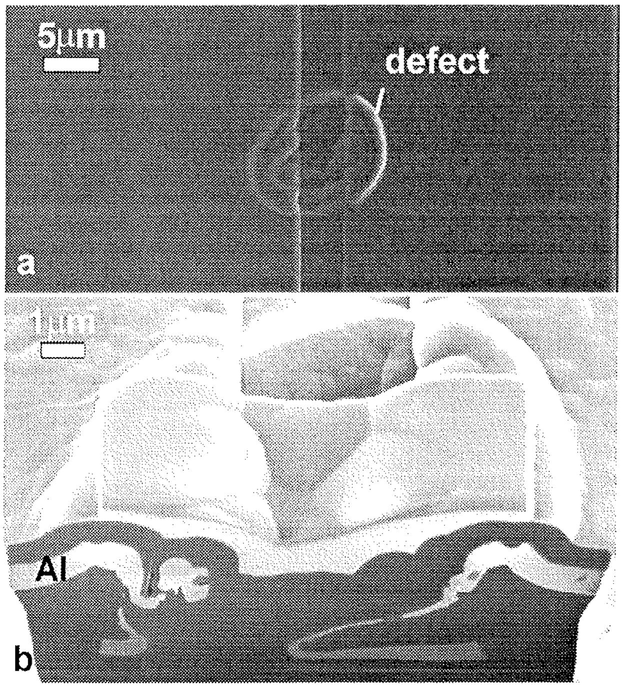

Fig. 4: *Top view (a) and cross-section (b) FIB images of a large defect localized by emission microscopy.*

The exact localization of the defect in the FIB is generally not so trivial as in the previous case because mostly no unusual topography is present on the surface. Also, the light spot seen with the emission microscope is larger than the actual defect so that some uncertainty exists on the defect position. Therefore the FIB investigation will often need a procedure consisting of the gradual milling of the crater through the failure site and the intermediate imaging on the crater sidewall. Figure 5 illustrates a conductive residue between two Al lines which is revealed in this way.

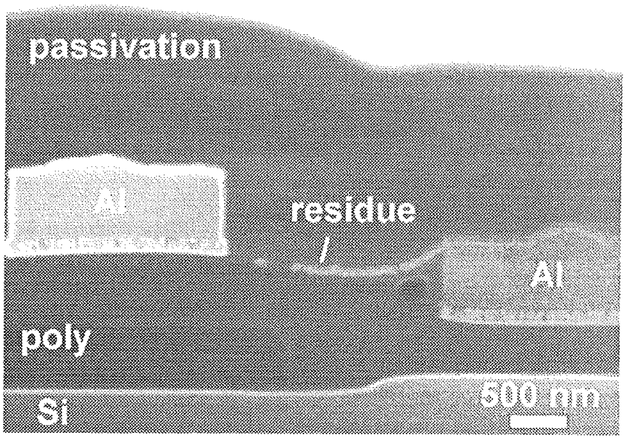

Fig. 5: *FIB cross-section showing a conductive path between two Al lines at a failure position which is revealed by emission microscopy. (Because the poly line is floating, it shows a dark contrast).*

Light emission in the emission microscope can also be due to failure mechanisms which cannot be revealed by cross-section FIB imaging. E.g. gate oxide pinholes cannot be seen on the FIB images because of its limited image resolution. To fully characterize such defects, investigation by transmission electron microscopy is necessary. For the site-specific preparation of the thin TEM specimens, the FIB specimen preparation technique is indispensable /8,9/.

3.3 Failures localized by voltage contrast

Electrical testing can be used to localize open contacts or vias. In unpassivated devices, i.e. test structures or devices which are depassivated, voltage contrast /12, 13/ can directly reveal the position of open contacts.

Figure 6 illustrates the technique for a large contact chain. The different probe pads above the chain are connected to different nodes in the chain and allow the electrical testing of parts of the chain. On the initial image (Fig. 6a) part of the probe pads and of the Al lines are dark, indicating that they are connected to open contact plugs in the chain and are hence floating with respect to the silicon substrate. The higher magnification image (Fig. 6b) shows also the presence of dark Al interconnections in the chain. The cross-section image (Fig. 6c) confirms that for these dark Al interconnects both contact plugs are open due to a very irregular etching of the contact holes. Because of the bad etching also the W filling of the contact holes is very poor. The Al interconnect on the left of the cross-section image has only one open contact and was therefore still bright on the top view image. Therefore the voltage contrast technique on such contact chains is not very sensitive to reveal opens because this requires that both contacts are simultaneously open, i.e it will work only well on rather bad chains.

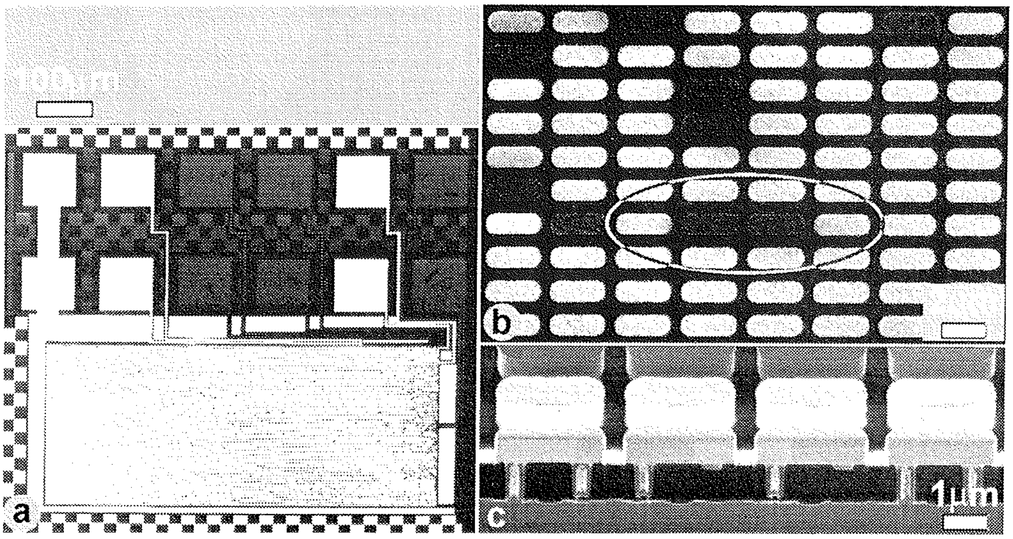

Fig. 6: Voltage contrast experiment on a contact chain test structure: (a) the initial top view image of the chain, (b) detail of the chain at higher magnification and (c) FIB cross-section image through the contacts encircled in (b).

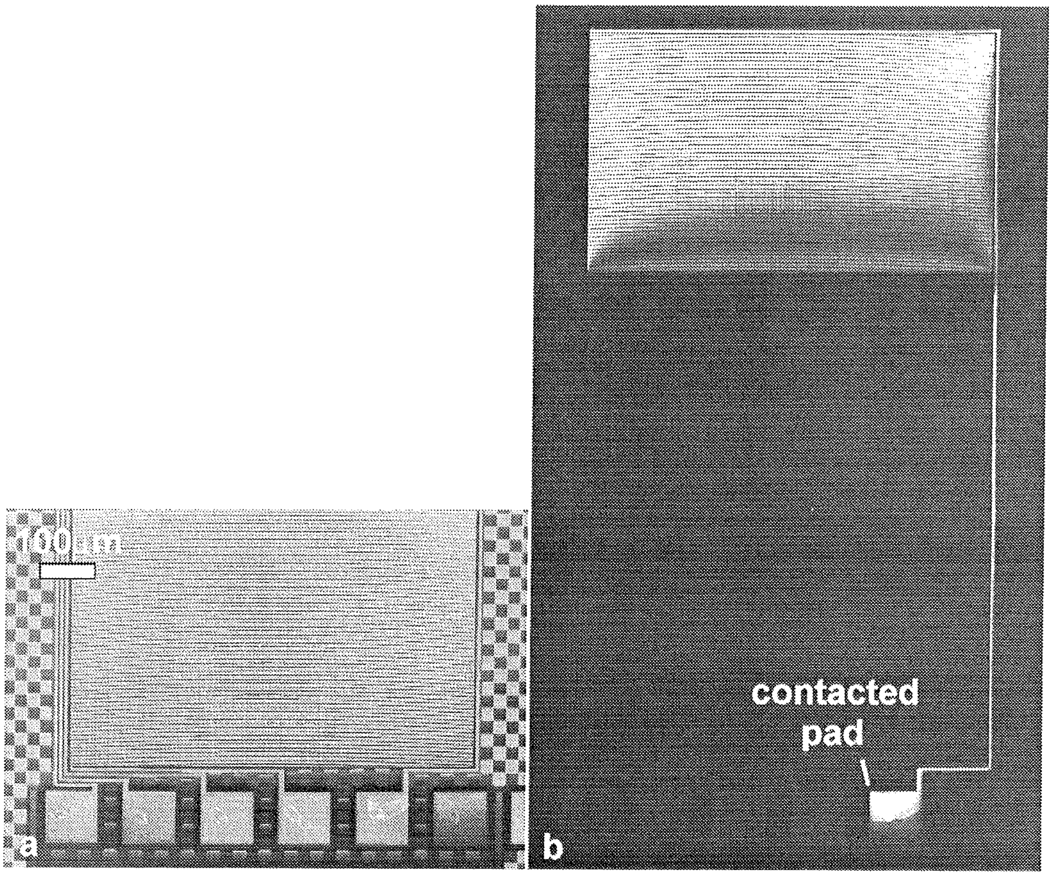

Fig. 7: Initial top view FIB image of part of a via chain (a), and (b) the full chain after contacting the marked pad to the substrate so that the open via position can be revealed.

This limitation of the voltage contrast sensitivity does not hold for via chains. Such chains are fully isolated from the silicon substrate. Figure 7 shows the initial FIB image of part of such a chain. All Al shows initially a brighter contrast than the dielectrics. This is actually only a transient effect. Due to the charge build-up also the Al will become dark after a few image scans. Subsequently a probe pad which is connected to the start (or end) of the chain is contacted to the substrate. This is done by milling a small hole through the pad into the substrate. Generally the redeposited material will already result in a sufficient contact between the pad and the substrate. To ensure better contact the hole can also be filled with some Pt deposition. Due to this connection the pad becomes bright and also the Al line and the chain until the open contact will now show a bright contrast (Fig. 7b). Cross-section imaging can then be done at the position of the open contact (Fig. 8). The bright line at the bottom of the open via indicates the presence of an isolating material between the W filling and the lower metal. Most probably this is due to a too undeep etching of the via.

The use of a low charge dose during the localization of the failure site is essential. A too high charge can result in a discharge during the FIB imaging of the charge build-up on the floating metal so that the original failure cause is destroyed (Figure 9). This risk is particularly high for single vias connected to large Al areas. In such cases the discharge often occurs during the milling of the crater for the cross-section imaging for which a rather high beam current must be used. Therefore the connection to the substrate through neighboring metal tracks or by ex-situ deposition of a conductive gold layer should be considered before milling the crater.

Depending on the nature of the bad contact, a too high current during the localization can result in leakage through the failure site so that the voltage contrast is lost. Therefore moderately bad contacts are generally difficult to reveal.

It should also be remarked that once a cross-section is made the voltage contrast is generally lost (see e.g. Fig. 6c). This is due to the redeposition of the sputtered material between the small Al lines so that a conductive path to the substrate is formed.

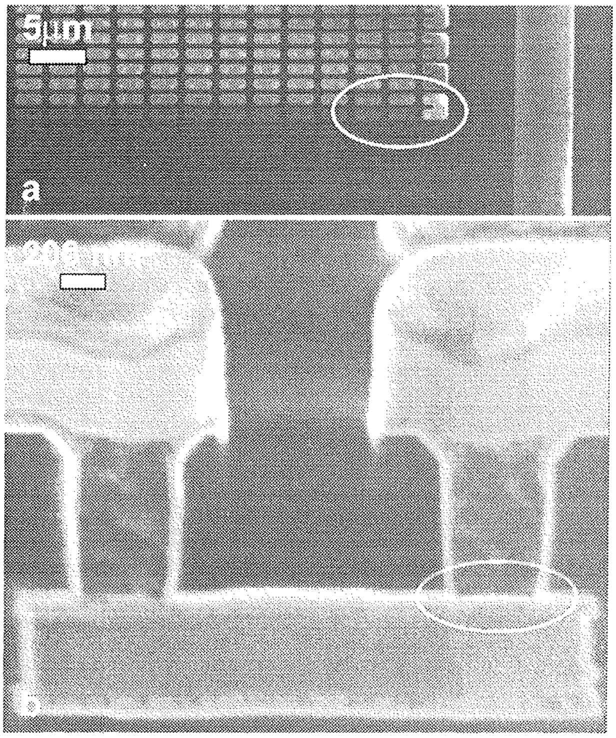

Fig. 8: *Higher magnification (a) of the position of the open contact in the via chain shown in fig. 7, and (b) cross-section image through the open via revealing the presence of an isolating material at the bottom of the via.*

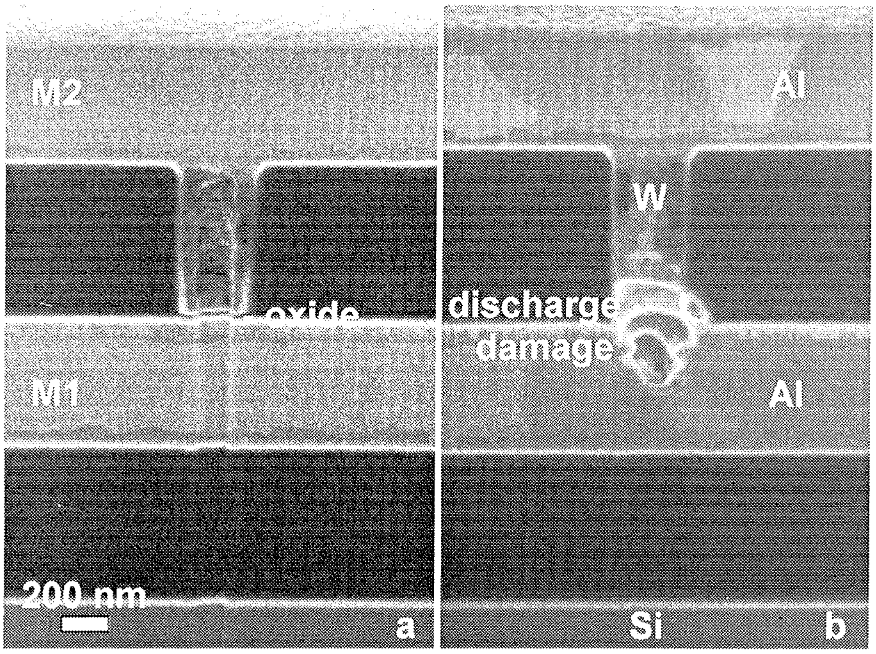

Fig. 9: *FIB cross-section image through M1-M2 Kelvin structures in which the vias are open due to too undeep etching: (a) the upper metal was contacted to the substrate prior to the preparation of the cross-section, the cause of the open is clearly seen; (b) the upper metal was not contacted resulting in a discharge of the charge build-up on the large M2 plate during the milling of the cross-section so that the real cause of the open is destroyed.*

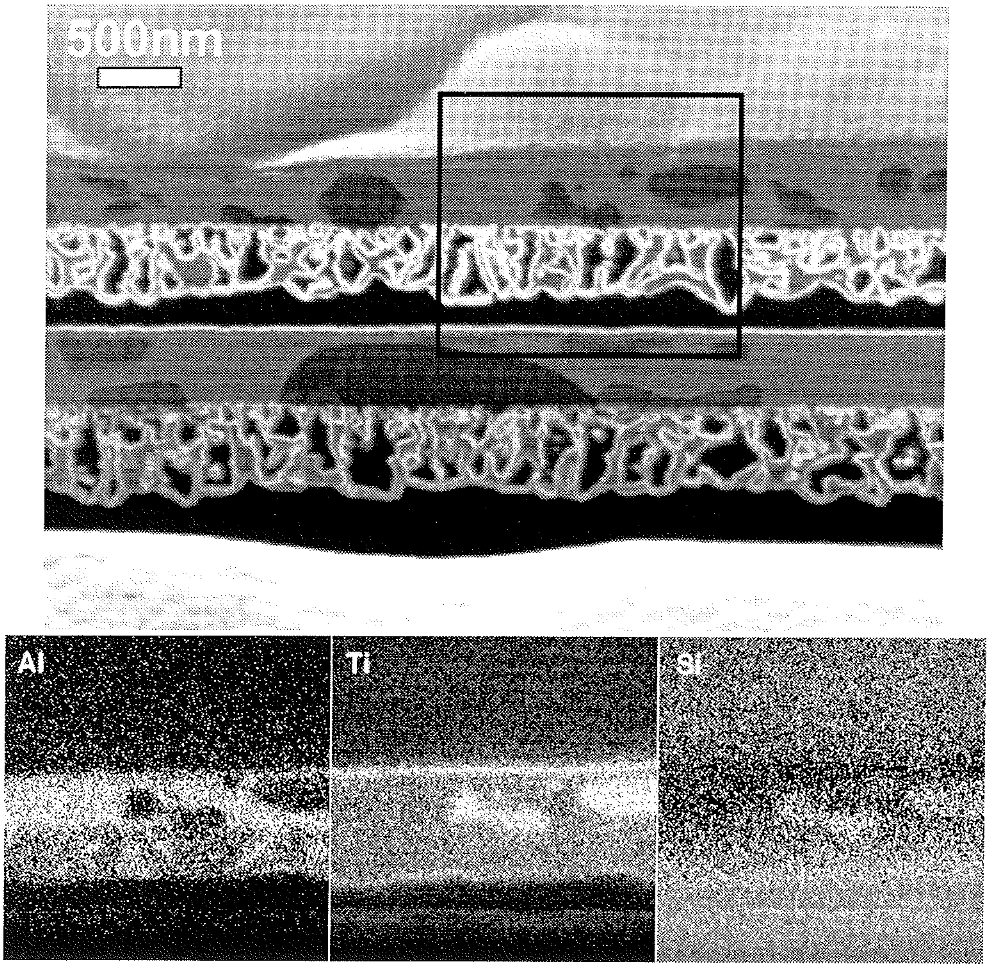

Fig. 10 FIB cross-section image (a) through a two metal metalllisation structure which was heated to 575°C and (b) Al, Ti and Si Auger mappings of the area marked in (a).

3.4 Chemical analysis by Auger spectroscopy

Chemical analysis at the failure sites is often required to fully understand the nature of the defect. This is possible in-situ if a secondary ion mass spectrometer (SIMS) is available or by energy dispersive X-ray spectroscopy (EDX) in dual-beam FIB systems (i.e. combining a FIB and a SEM column). Ex-situ analysis is possible by e.g. Auger electron spectroscopy.

Fig. 10 shows Auger mappings of Al, Ti and Si on a FIB cross-section through an Al interconnect structure which was heated to 575°C for 30 min /15/. The formation of Al-Ti-Si inclusions in the Al and the diffusion of the Al in the dielectric layer can be seen.

4. Conclusions

The focused ion beam technique has a wide range of applications for failure analysis studies of electronic devices. Except of the discussed topics other possible applications are, e.g., local depassivation for e-beam testing, deposition of probe pads for electrical testing, or investigation of electromigration test structures /16/.

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