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CHARACTERIZATION OF MIRROR-LIKE WAFER SURFACES USING THE MAGIC MIRROR METHOD

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An awe-inspiring mirror used for centuries in religions of the Far East has been polished and brushed up to become a powerful scientific tool. This "magic mirror", very simple and non-destructive, transforms latent damage, scratches, waviness and other flaws on mirror-like surfaces into visual images using the "Makyoh" principle. The technique detects undulations of a few nm over a distance of about 0.5 mm. It has recently been used to characterize highly finished mirror-polished large diameter Si wafers for ULSI applications, replacing the laborious and unstable naked eye wafer inspection lines. Our studies have shown that the technique is also very useful for monitoring surface sensitive IC processes such as epitaxy, chemical vapor deposition, rapid thermal process, ion implantation, etc.

1. Introduction

Demands for non-destructive instantaneous surface characterization and in-line monitoring methods have been increasing recently, since perfect mirror-like flat surfaces are required more and more these days. This is especially true for Si/compound-semiconductor wafers for advanced VLSI and ULSI applications, hard discs and magnetic heads, the working dimensions of which are now approaching values in the order of 0.1 μm, and sometimes in the order of nanometers.

It has been recognized that the quality of the starting wafers is very important in improving the properties and yields of VLSI and ULSI circuits. Various characterization methods for polished surfaces have been developed and applied in quantitative and qualitative ways. Most of them are destructive, such as the etching of defects, thermal treatment of latent micro-defects, and chemical or physical etching of wafer surfaces. Surface topography and non-destructive methods such as X-ray analyses [1,2] and optical methods (including Newton ring observation) [3–5] have also been frequently applied. However, all of these currently available methods have been of limited use due to their complexity or their lack of sensitivity or reproducibility. Therefore, it is desirable to develop a noncontact, nondestructive surface characterization tool with good sensitivity and flexible, rapid full view imaging capability.

The magic mirror is an optical method based upon "Makyoh concept". "Makyoh" means "wonder-mirror", and is a simple flat mirror made

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of brass. It is truly featureless when looked at directly, but when it reflects the sun or moonlight, bright images of Buddha appear on a dark temple wall. The traditional technology of "Makyoh" has been passed on from person to person for many centuries.

The "Ma-kyoh" principle has been applied to the evaluation of Si wafers and various wafering processes such as polishing, slicing, and cleaning [6,7]. The concept was developed into a new optical observation method for easier and reproducible operations. It has been successfully applied to characterize various Si wafers [7,8] used in ULSI applications with the highest finish. This paper describes the recent development of the magic mirror method, reviewing some of the results obtained in the evaluation of mirror polished Si wafers for ULSI device fabrication processes.

2. The magic mirror method

There are still some ambiguities about the basic principle of "Makyoh". Either mirror surface contour irregularities or reflectivity fluctuations, or both, give hidden images in reflected rays. For this discussion, light penetration through mirrors was not considered because of the high reflection at the surface. Numerous observations of mirror polished Si wafers have shown that most of the image patterns were due to the slight waviness of the surface and very few were due to reflectivity differences. This was clearly seen by the changes of bright/dark reflected mirror images (image patterns) when the distances between the mirror and the images are changed. The reflection differences were mostly due to dirt, oil or Teflon transferred from tools.

The most simple example of the "Makyoh" concept due to surface contour is shown in fig. 1. Reflected light at a concave surface tends to focus on a screen, and thus one observes an image pattern resulting in dark areas and a bright area in between, like a concave mirror. On a convex surface, an opposite image pattern is observed. Since surface contours are generally assumed to be combinations of convexes and concaves, or exact flats, observed image patterns on a screen are

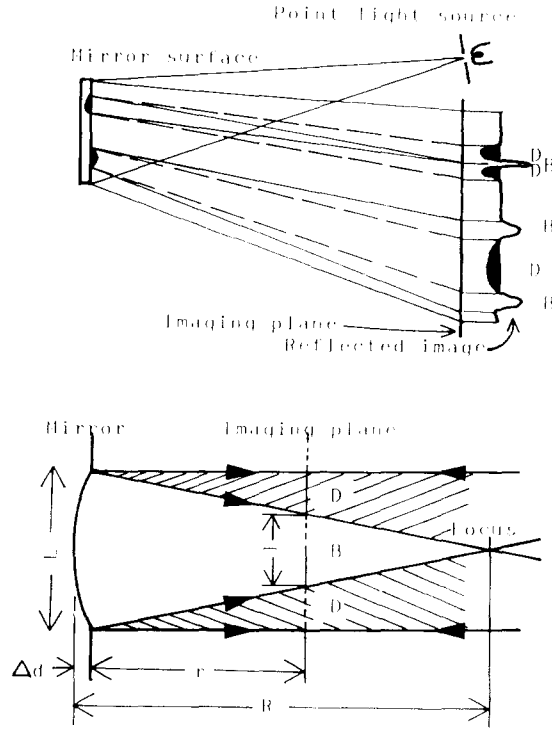

Fig. 1. Concept and principle of "Makyoh". In this figure, D and B stand for dark and bright areas, respectively.

composed of a combination of image patterns corresponding to original surface contour of the wafer. Even sharp scratches are, for instance, assumed to be composed of two convexes and a concave in between with very small radii. These give image patterns of dark scratch lines in a background, since a bright line is scattered off due to the small curvature. The sensitivity of the method can be expressed by the amount Δd and the curvature of surface P and estimated as follows. Since $R = [L/(L - l)]r$ and $\Delta d = L(L - l)/8r$ as derived from the figure where $P = 2R$, setting value of $r = 6$ m and typically observed values of $L = 0.75$–1 mm and $L = 2l$ results in $\Delta d = 6$ nm and $P = 24$ m. In the extreme case, $P = 100$ m could be observed.

A "Makyoh visualizer" was built in-house at Matsushita Electric Industrial Co. Ltd., for a research evaluation, and also introduced from Yamashita Denso Tokyo, Japan, YIS-150 for evaluation of mass-production inspection lines. In

the commercial model, image patterns of Si wafers (obtained from various vendors) were displayed on a TV screen and could be instantaneously recorded on VTR, if needed for future exchanges of opinion or discussions among vendors and customers. In addition, improved sensitivity and functionality were realized by the introduction of green LEDs and CCD imagers which are very sensitive to green light.

Analyses of the slicing and polishing processes indicated that crystal defects might be present beneath saw marks, lapping marks and dimples. A following experiment was carried out to see the presence of defects. Slight scratches were made in a backsurface of a wafer by a diamond point scriber at various loads. As the load of the scriber increases, brighter lines appear on the image pattern and the amount of bending of the Si wafer increases. This shows that scratches induce tensile stress at the backsurface and make the Si wafer slightly concave locally. After breaking the wafer into 4 pieces, both sides of each piece were etched in Secco solution for 1 to ~ 10 min. Observed surface irregularities of the wafer before and after etching are shown in fig 2. Parallel bright lines before etching were clearly formed by the concavities made by slight tensile stress caused by scratches in the back surface. A white spot in the figure was a dimple. After etching for 1 min, no bright line was observed but after etching for a longer time, brighter lines reappeared as shown in fig. 2B.

When scratches were made in the front surface of the wafer, dark lines were initially observed instead of bright lines and then bright lines appeared after etching as described above. These were due to (1) that etching quickly released the residual stress and thus the front surface deformation, because the etching rate was very high at scratched or damaged areas, and (2) that prolonged etching engraved the front surface along the defects which reached to the front surface from the backside scratches (or along the scratches in the front surface) and thus made concavities.

Figs. 3 and 4 show some of the typical image patterns observed from wafers received from various Si vendors. YIS-150 can pick-up, for instance, very shallow concavities of 0.38 μm depth over about 10 mm span and 0.05 μm over about 1 mm span, corresponding to the radius of curvature of about 15 m and 2 m respectively (as shown in fig. 3). These depth profiles were measured by a surface profilometer. In fig. 4, the various surface deformations of as-received wafers observed by the monitor over a certain period of time were shown. Bright lines and areas correspond to surface concavity and dark lines and areas to surface convexity. Most of observed deformations are saw marks (fig. 4, part 1), polishing/lapping marks (fig. 4, parts 5 and 6), backsurface damage irregularities

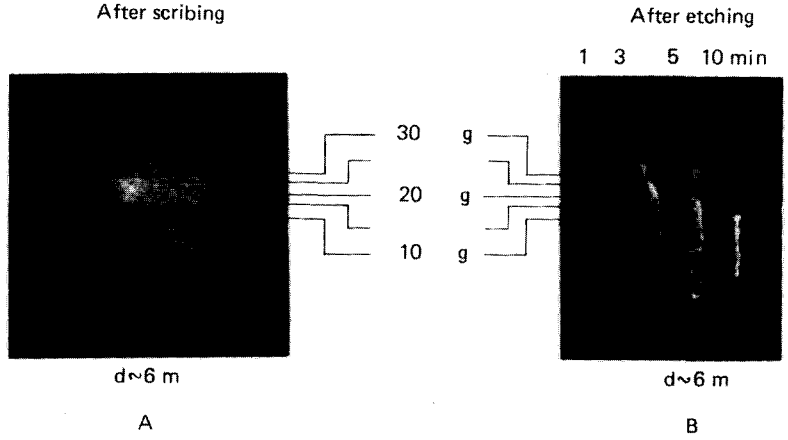

Fig. 2. Microdeformation in the front surface caused by scribing the backsurface of a 75 mm diameter wafer.

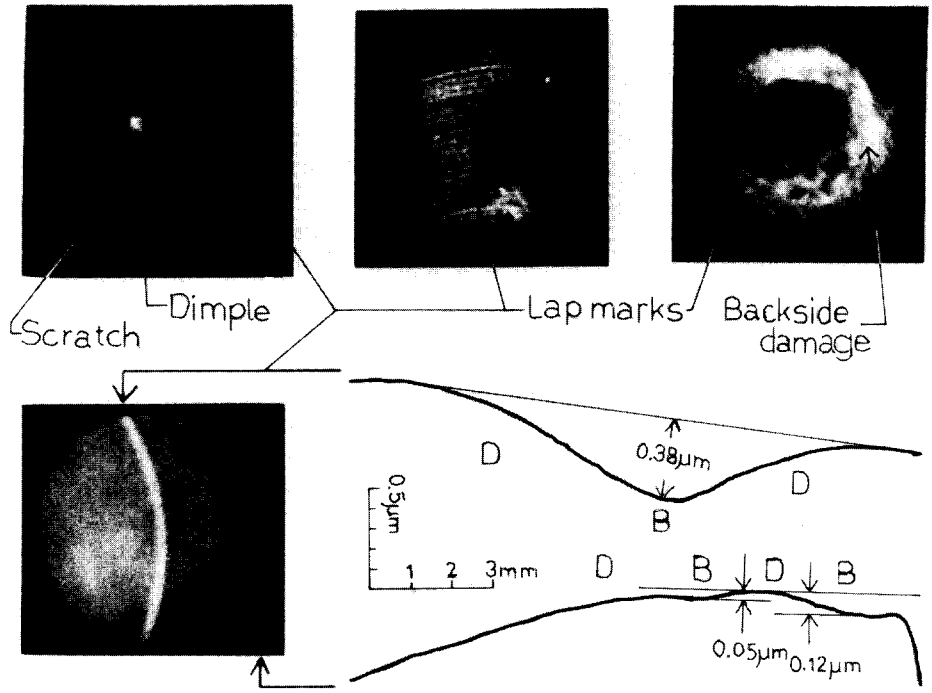

Fig. 3. Representative types of microdeformation in the surface of 75 mm diameter Si wafers.

(fig. 4 parts 2, 6 and 10), dust crawl during epi growth (fig. 4, part 4), bubble in wax during polishing (fig. 4, part 4), bubble in wax during polishing (fig. 4, part 8), scratch at the back surface (fig. 4, part 7) and strange marks due to unknown causes (fig. 4, parts 3, 11 and 12).

It may be worthwhile to note that flaws near the back surface as well as the front surface can be monitored by the magic mirror method. Among all the anomalies, the most commonly observed flaws were dimples. Generally, no crystal defect is expected to associate with dimples, but when dimples are generated by accelerated mechanochemical etching of defects, one might have to worry about crystal defects beneath dimples. Even then, dimples were generally found to be rather harmless since the number of dimples per typical 125 mm Si wafer was small (2–3 at most) and their sizes less than 1 mm in diameter. Thus, even if some crystal defects were associated with them, they were not as harmful as those due to scratches, since the areas covered by them were negligibly small. Scratches and stains have sometimes been observed. These flaws, mostly due to wafer mishandling, were found to be directly related to the yield loss of finished devices. Saw marks which could easily be confused with polishing marks have been seldom observed nowadays. Saw marks are very harmful to IC device performance since crystal defects were latent and hidden beneath them. Latent stress around saw marks can provide potential sites for formation of stacking faults and dislocations during subsequent heat treatments.

Polishing marks were mostly formed by surface irregularities, fibrous materials and textures of polishing cloths. The magic mirror was so sensitive that even a change of polishing cloths led to the different appearance of polishing marks. Polishing marks resulted in a slight waviness of the surface without any crystal defects and residual stress, and thus they are not as harmful as saw marks. Lapping marks can be harmful since rough grinding may result in large defects which may not be eliminated during subsequent polishing process

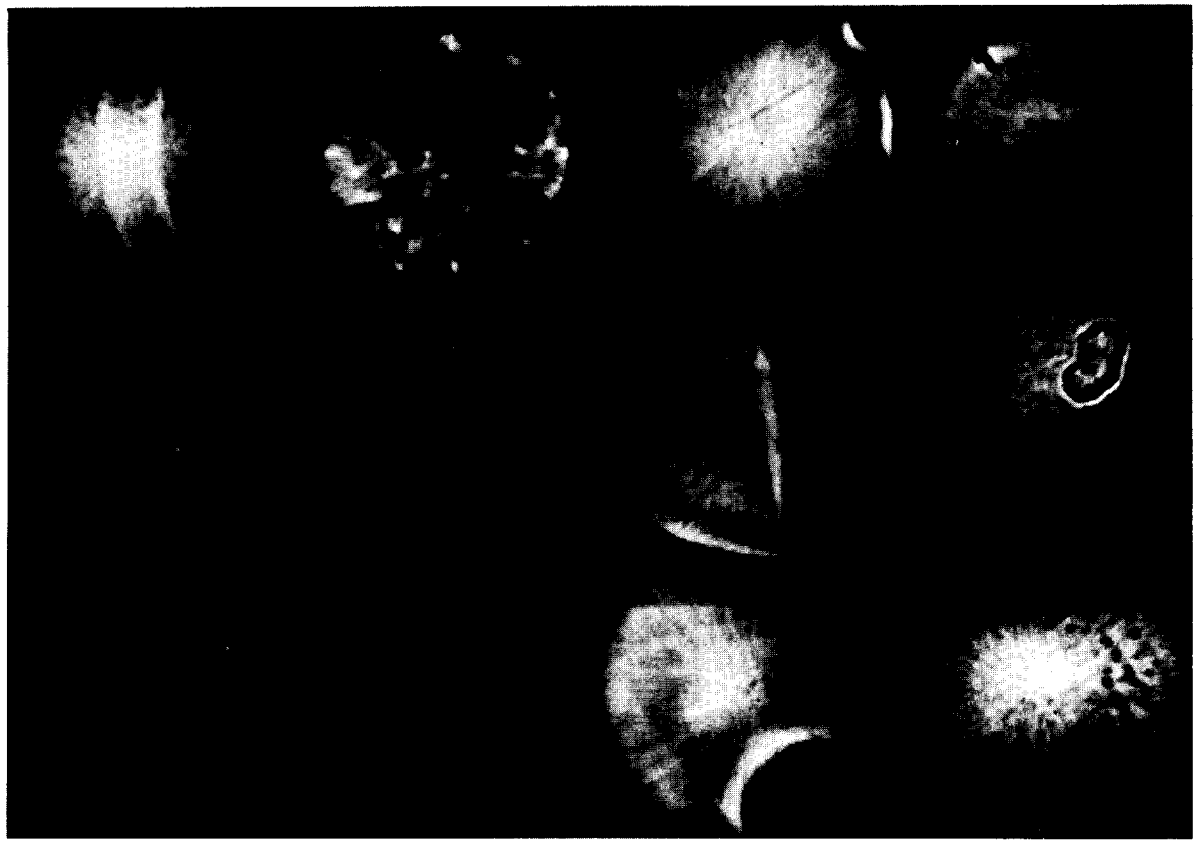

Fig. 4. In-line monitoring of as-received Si wafers. Parts 1–4: 1st row, left to right, respectively. Parts 5–8: 2nd row, left to right, respectively. Parts 9–12: 3rd row, left to right respectively. In this figure, observed deformations are saw marks (part 1), polishing/lapping marks (parts 5 and 6), backsurface damage irregularities (parts 2, 6 and 10), dust crawl during epi growth (part 4), bubble in wax during polishing (part 8), scratch at the backsurface (part 7) and strange marks due to unknown causes (parts 3, 11 and 12).

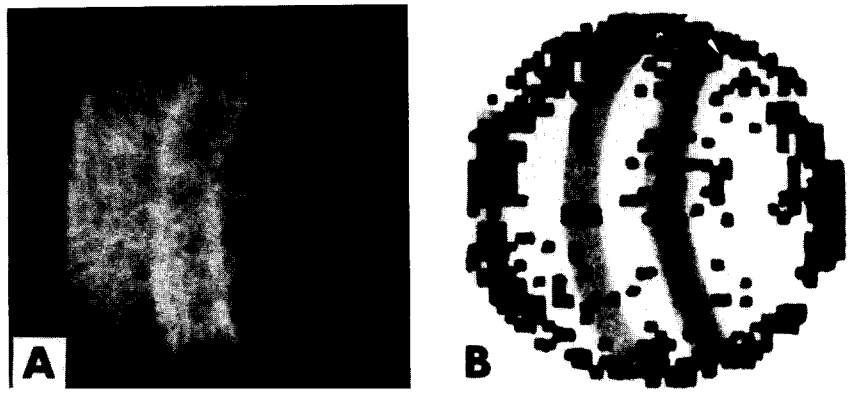

Fig. 5. Lapping marks and stacking fault distribution: (A) as-received; (B) after oxidation.

steps. Since polishing and lapping marks are hard to differentiate, one has to monitor the changes in image patterns for a period of time in order to see any symptoms of process variations and instabilities. Typical patterns of lapping marks are shown in fig. 3; their depth can be as large as 0.4 μm.

X-ray topographs of the deformation showed that backsurface damage irregularities, scratches, and some of the unknown deformations were accompanied by a slight lattice deformation and thus by the residual stresses. However, optical microscopic observation of oxidized and etched wafers showed that most of the deformations were proved to be harmless and some were related with crystal defects [9,10]. A typical example of the stacking fault formation after the dry oxidation at 1000°C for 1 h is shown in fig. 5. Stacking faults revealed by the Secco etching are shown by dots, and their distribution as shown by two gray bands in fig. 5B is in fair agreement with lapping marks in fig. 5A. This clearly indicates that some lapping marks are accompanied by latent mechanical damage. Some specimens with the residual strains (as shown in fig 4 parts 2, 4 and 7) showed an unusual denuded zone formation after three step annealing (fig. 6B). For the wafers (with an interstitial oxygen concentration of about 10^{18} atoms/cm^3 and unusual magic mirror image described above) as used in this experiment, no denuded zone is usually observed even after the heat cycle of 1100°C O_2, 4 h/800°C N_2, 16 h/1000°C N_2, 6 h [11]. When wafers with lapping marks were processed without proper care, a reduction of the yield of certain types of bipolar IC products was observed (as shown in fig. 7). In this figure, the yield of normal wafers was compared with that of the wafers with lapping marks. Emitter–base leakage problems due to the crystallographic defects were found to be the main cause of yield loss for the wafers with lapping marks. Numerous crystallographic defects were observed at the areas around saw marks (and lapping marks) after Secco etching, and their radial distribution and yield maps corresponded with each other fairly well.

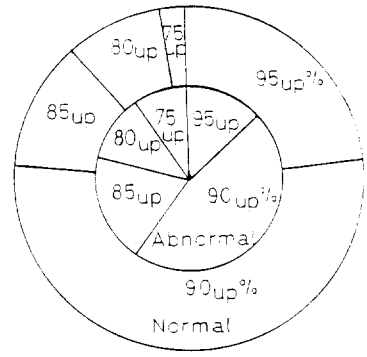

Fig. 7. Yield comparison between normal wafers and abnormal wafers with lapping marks.

Several years of fab Si wafer material evaluation by the magic mirror method led to a valuable conclusion. From time to time, there were sudden changes or drifts of the wafer image patterns in the course of monitoring. These were clear indications of some process changes, vendor's inter-fac-

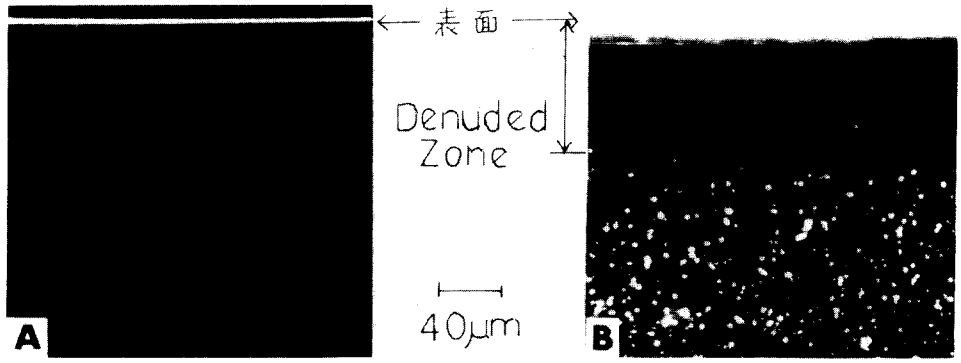

Fig. 6. Abnormal denuded zone formation after the heat treatment cycle of 1100°C O_2, 4 h/800°C N_2, 16 h/1100°C N_2, 6 h. $O_i = 9.7 \times 10^{17}$ atoms/cm^3; (A) normal, (B) With the residual stress.

tory differences (both process and location), instabilities, sometimes loose process control, or even in the worst case, unnoticed malfunctions in the wafering processes. Our experience has shown that, regardless of vendor, perfect wafers without any flaws are rare occurrences, although this was not such a serious problem as appeared at first. Therefore, it was concluded that one should not simply chase after complete perfection in image patterns, i.e., a featureless or textureless image pattern. Instead, one needs to obtain wafers with almost the same image patterns all the time, which assures that the wafers are manufactured under controlled and reproducible conditions. Moreover, flaws in the image patterns did not necessarily mean deadly defects for yields of IC production lines, as described above.

The magic mirror method was also applied to evaluate various device fabrication processes, such as epitaxy, chemical vapor deposition, plasma etching, rapid thermal processing, ion implantation, etc. For example, numerous slip lines with a few nm steps were clearly observed after the poor epitaxial growth (as shown in fig. 8). In addition, worm-like patterns (as shown in fig. 4) were also frequently observed after some epitaxial growth runs. These "worm crawls" were most likely formed by dust, inside the epitaxial reactor which, loosely sticking/rolling over the wafers, led to abnormal epitaxial growth. Abnormal epitaxial growth was also observed at crowns. Changes in the image patterns were clear indications of deviations from the normal epitaxial operating conditions. This technique has been proven to be very useful for quick conditioning of epitaxial reactors and daily monitoring of an epitaxial operation. Changes of wafer shapes after thermal treatment were observed (as shown in figs. 9A and 9B). Clean wafers without residual stress were not expected to exhibit any anomalous changes in shape.

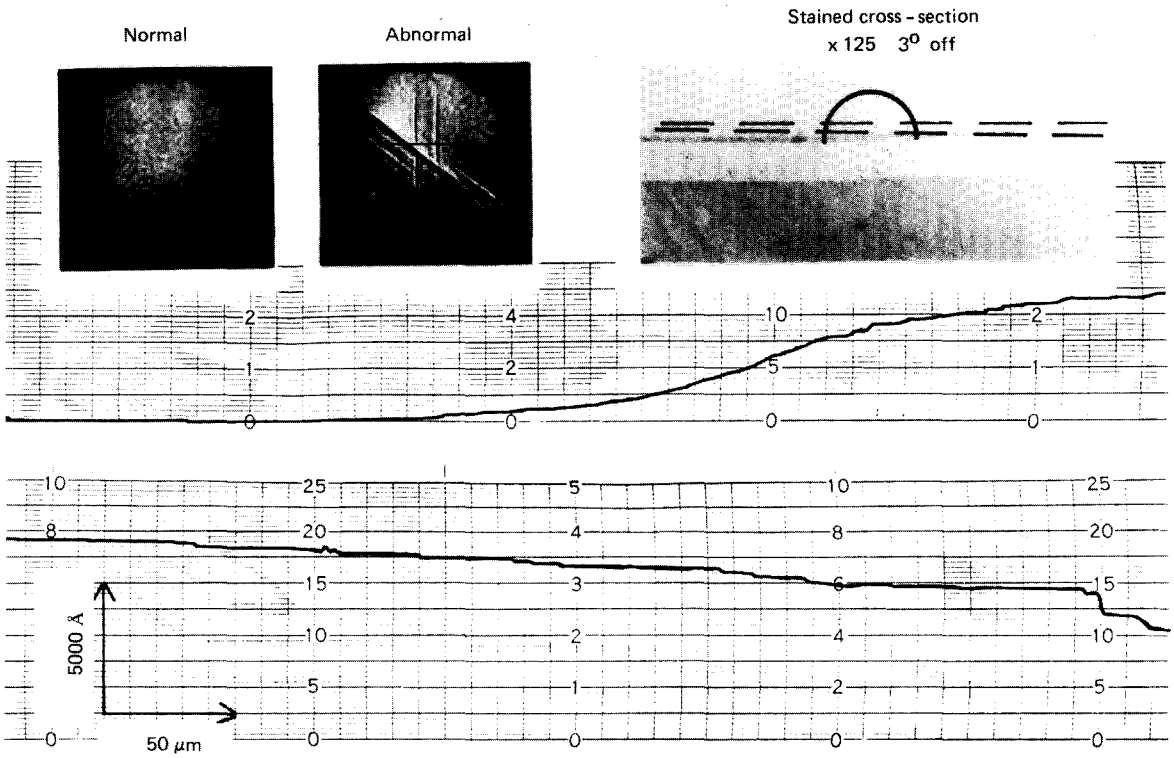

Fig. 8. Monitoring of slip lines formed in the epitaxial process.

However, some wafers did show strange deformation (which strongly indicates some problems in the starting substrates and/or device processing conditions). Defects like slip and dimples were still observable even after the patterning as shown in fig. 9C.

With the advances made in rapid thermal processing (RTP) during recent years, it has been thought necessary to carry out industry-wide evaluation of presently available RTP equipment. Yarling and Keenan [12] have recently reported their results from a round robin test to determine

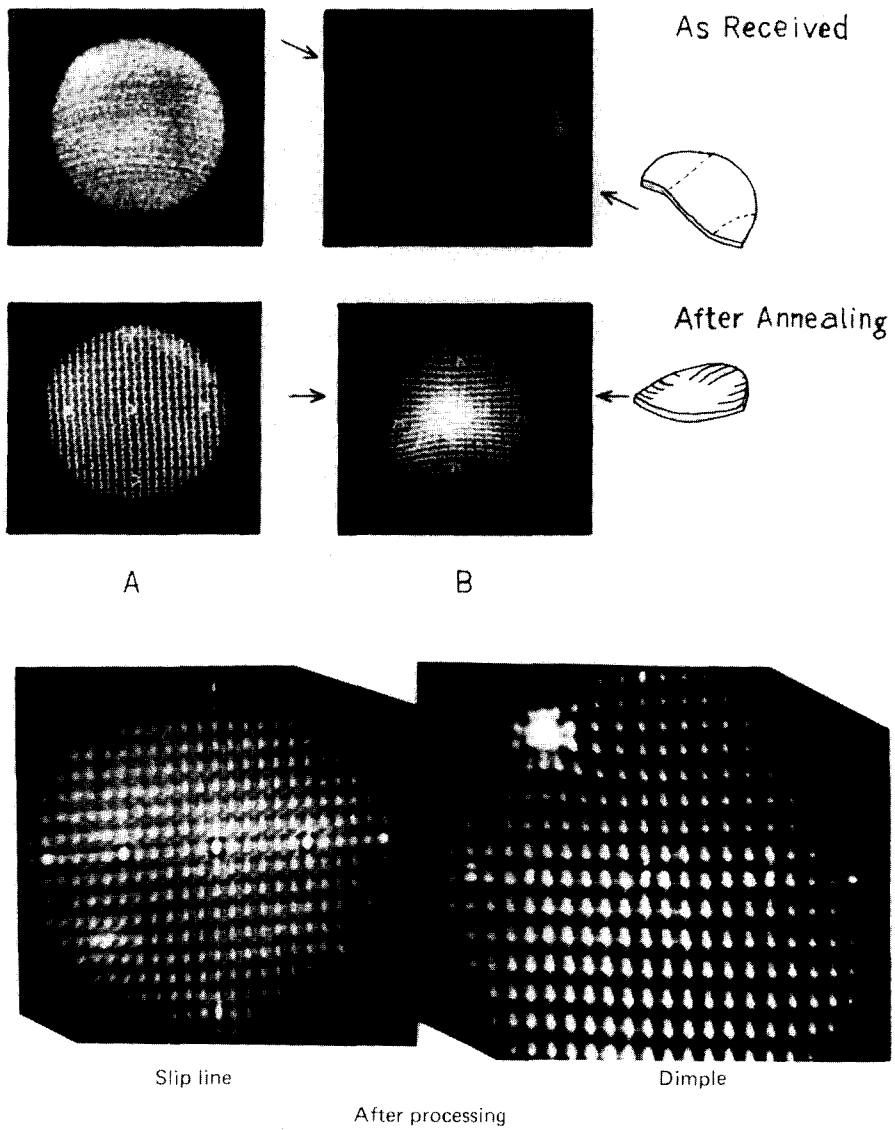

Fig. 9. Warpage changes and surface irregularity preservation during the IC fabrication process: (A) normal; (B) seriously warped wafer; (C) wafer with slip/dimple.

various process-induced defects induced into the wafers due to the RTP process. In their actual experiment, 150 mm diameter P-type (100) wafers ($\rho \sim 10$–$20\ \Omega$ cm) with no screen oxide were implanted on a batch implanter. The implant conditions were $5 \times 10^{15}/cm^2$ of As^+ at 80 keV. Each RTP equipment vendor (total number of companies that participated = 8) processed four wafers at 1100°C for 5, 10, 15 and 20 respectively. These wafers were analyzed with full-wafer evaluation for RTP-induced defects by wafer flatness, magic mirror inspect, and thermal wave measurements.

All the wafers measured using the magic mirror technique exhibited saw marks and wafer scribe marks which were made after implant and before rapid thermal processing. In addition, several wafers showed polishing marks. Also observed in some wafers were slip and warpage resulting from the rapid anneal process. Warpage is evident in wafers having as little as a 10 s anneal (Vendors E, F and G) with slip occurring in as little as a 5 s anneal (Vendors E and G). The results obtained by the magic mirror technique for wafers processed by all vendors are summarized in table 1.

Monitoring of GaAs, InP and other compound semiconductor wafers also showed image patterns similar to those shown in figs. 4 and 5 though image patterns were much more complex and less clear because of more defects. Recently, the magic mirror method has been extensively applied for improvement of wafering processes in compound semiconductors.

Table 1
Visual results from magic mirror inspection for various implant rapid thermal annealed wafers (implant conditions: $5 \times 10^{15}/cm^2$ of As^+ at 80 keV; RTA conditions: 1100°C for 5, 10, 15 and 20 s respectively)

RTP anneal time (s)	Vendor							
	A	B	C	D	E	F	G	H
5	–	–	–	–	S	–	S	–
10	–	–	–	–	S, W	S, W	S, W	–
15	W	W	–	W	S″, W″	S, W	S	W
20	S	S, W	–	W″	S″, W″	S, W	–	W

Note: W = moderate warpage; W″ = severe warpage; S = moderate slip, S″ = severe slip.

3. Conclusions

The magic mirror method, based upon the centuries-old "Makyoh" principle, is proven to have a very high sensitivity to the microtopography of mirror-like surfaces. It can detect small undulations of some 10 nm over a few mm span and some nm over a half mm span. In the evaluation of Si wafers, various surface flaws such as dimples, orange peels and slips on a whole wafer are made readily visible. This technique is useful in optimizing various wafering processes. Since it is sensitive to surface microtopography, it can be used to monitor any surface condition sensitive to IC processes such as epitaxy, chemical vapor deposition, rapid thermal processing, plasma etching, and ion implantation.

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