LASER SCANNING TOMOGRAPHY : A NON DESTRUCTIVE QUALIFICATION TEST FOR SEMICONDUCTORS

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LASER SCANNING TOMOGRAPHY : A NON DESTRUCTIVE QUALIFICATION TEST FOR SEMICONDUCTORS

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RESUME - Parmi les différentes méthodes de caractérisation des défauts dans les wafers de semiconducteur, les techniques par infra rouge doivent être remarquées pour leur caractère parfaitement non destructif. Le développement récent de la tomographie laser à balayage permet d'obtenir des images de haute résolution des dislocations décorées et des microprécipités. L'exploration du matériau dans les trois dimensions est réalisée avec une grande précision jusque dans le voisinage immédiat des zones actives des composants. On étudie l'observation des micro défauts et particulièrement les substrats GaAs de différentes natures. Des images à l'échelle microscopique révèlent des précipités de taille bien inférieure à la limite de diffraction optique. D'autres résultats ont aussi été obtenus sur InP, CdTe ou Si ; la plus part des semiconducteurs classiques peuvent être analysés par tomographie laser à balayage ce qui fait de cette méthode un outil précieux d'investigation.

ABSTRACT - Among the various physical approaches of the semiconductor wafer defect characterization a special attention is to be payed to the infra red imaging techniques which are prefectly non destructive . Recent developement of the Laser Scanning Tomography will be emphasized because it gives highly resolved images of decorated dislocations and microprecipitates . Three dimensional exploration of the material is allowed with a large accuracy and possibly close to the active regions of the circuits. Observation of micro defects are reviewed , especially concerning GaAs materials of various origins and constitutions. Microscale images enable us to reveal very small scatterers even if their size is much smaller than the optical diffraction limit. Results obtained on other semi conductors such as InP, CdTe or Si will also be reviewed ; most of the conventional semiconductors are relevant to this powerful technique which is a unique means of investigation.

1 - INTRODUCTION

It is known that compound semiconductors (such as GaAs for instance) suffer a large diversity of crystallographic defects induced by the delicate interface equilibrium during the growth process and also by the post growth cooling transient. These defects diversely affect the behavior of the elaborated circuits and leads to a scattering in the specifications /1,2,3/ .

In order to control such flaws and also to undertake a feedback on the growth technology , several inspection techniques were suggested which are more or less destructive of the surface of the wafers; also ingot or wafer annealing is often intentionally used to improve the uniformity of the technological process /4/.

Twelve years ago it was suggested by Tajima /5/ that light scattering ultra microscopy (Tyndall effect) could be a powerful tool for investigating defects and especially metallurgical faults in GaP crystals . This technique was afterwards largely improved by Ogawa and coworkers /6,7,8,9/ who invented a revamped experimental set-up incorporating new devices like the laser and the computer . They used it to explore quartz materials as well as GaAs , InP , CdTe etc...

This technique was called Laser Scanning Tomography (LST) because a focused laser beam is introduced in the sample and linearly moved in order to generate a virtual plane of illumination . The corresponding light beam image is collected by a camera having a line of sight at 90° to the beam direction, the successive images being assembled by a dedicated computer . This method is attractive because it gives three dimensional capablility and is non destructive. The performances in contrast sensitivity and spatial resolution are especially high. To our best knowledge we are presently the only laboratory outside Japan that is equipped and experienced for such analysis.

From 1985 up until now , several studies were reported /10,11,12,13/ from several laboratories , they all refer to large scale (even wafer scale) images on GaAs materials; they provide us with detailed and complex distributions of bright defects the origin of which is questionable even if a satisfying general correspondence is found with other classical investigations such as surface chemical etching SCE /14/ , X ray topography XRT /12/ , infra red transmission IRT /15/ or cathodo/photo luminescence C/PL /16/ .

We have used the LST method (see Ogawa /17/) with the essential improvement of the optical configuration in order to observe sub-micron scale particles: higher optical magnification (typically X 40 or larger) of the camera leads to a field of observation as small as 220x220 mm (frame memory 512x512 pixels) at a maximum distance of 5 mm from the laser beam input face. The tomographical "plane" thickness was also improved by a sharper focusing of the laser beam ; the minimum thickness achieved is 10 µm and this plane is adjusted with the focus plane of the camera objective (the thickness of which is also 10 µm). The wafer surface can be approached to within 10 µm without introducing major perturbations in the image. In that configuration of reduced field, the scanning of the laser beam can be introduced simply using a vibrating mirror thus providing a "live" image on the TV monitor. A more reduced scale of analysis (down to the diffraction optical limits) allows us to discover the ultimate objects giving rise to the scattering in GaAs bulk material : they are all reducible to small "droplets" of condensed foreign atoms in the matrix .

These aggregates are found either along the dislocation path as decoration precipitates (DP) or in the dislocation free zones as clouds of randomly distributed microprecipitates (MP) : these two kinds of defects are isotropic Rayleigh type /18,19/ scatterers ; they are the only objects revealed by LST , no evidence is found for a contribution of the EL2 centers /20,21/ in the scattering mechanism /22,23,24/ .

The presence of microprecipitates in LEC grown GaAs has been also revealed by several methods (see Stirland /25/). For precipitates much smaller than 1 µm laser scanning tomography (LST) is of special interest owing to its ability to detect individual scatterers which are smaller than the diffraction limit; it is also well suited for a 3 dimensional visualisation of these defects. We studied by LST technique different types of SI LEC GaAs materials, namely undoped, Cr or In doped, unannealed or ingot annealed.

In this review communication we intend to comment the present state of the art in this domain of defect imaging especially dedicated to semiconductor wafer inspection. Of course GaAs is not the only material amenable to such investigation methods : InP , GaP , CdTe or even Si itself give rise to unexpected features of hidden flaws .

2 - EXPERIMENTAL

The Laser Scanning Tomography (LST) experiment /17,26/ is sketched in Fig. 1- : a focussed infra red laser beam is introduced in the wafer through a flat section and parallel to the faces ; the light scattered by the internal flaws along the beam path is collected by a TV camera and the image of this "optical window" is sent to a computer which selects the central TV lines ("TV window") ; then the sample is moved by stepper motors ("step window") and the total image of the virtual scanning plane is reconstructed and displayed as sketched by Ogawa /17/ in Fig. 2- . Three dimensional information can be achieved by simply changing the position of the tomographical plane .

This method allows a large amplification of the contrast of the image , it is perfectly non destructive and does not require any vacuum or low temperature facility . A macroscopic scale image takes a matter of minutes whereas microscopic images 2x2 mm are live TV images . It still remains that the effective thickness of the observation plane is determined by the diametre of the laser spot on the sample (typically some 50 µm) .

It was shown /10/ that the scattered intensity obeys a l-4 dependence which is typical of a Rayleigh isotropic scattering . The very low "absorption" coefficient a of semi insulating GaAs (2< a < 0.5 cm-1) in the l > 1 µm range enables penetration in the wafer to large distances (some cm) which makes it possible to inspect 2" wafer, using a YAG laser (1.06 µm) . Reducing the laser beam diameter down to 10^1µm allows generation of very thin tomographical planes. Lateral resolution for detecting the presence of a scatterer is very high provided that the scattering yield is effective: particles as small as 20 Å (macromolecules) were actually revealed by ultra microscopy in colloidal solutions /27/ .

This perfectly non destructive and accurate method was essentially used at a macroscopic scale ; it revealed very detailed cell structures in undoped GaAs and also dislocation clusters in GaAs-In, the comparison of these LST images with other images is quite satisfactory, keeping in mind that the referred volume is of limited thickness and adjustable in the bulk whereas other methods refer to the region close to the surface (EBM , C/PL , SCE and reflexion XRT) or to the whole thickness (transmission

XRT , TEM or IRT). The origin of the scattering was initially attributed to refractive index variations /28/ or to EL2 concentrations /29/. The present work definitively confirms with high resolution images that scatterers are microprecipitates condensed on dislocations or distributed in the volume as clouds of particles . As stated by Skolnick the deep center EL2 does not contribute in the scattering even if a correlation is found with a through a power 4 dependence /10/ .

If the beam path is kept very long in order to get cm scale images then absorption and light losses usually introduce a progressive reduction of the laser beam intensity along the distance and the LST image becomes unbalanced : this disadjustment can be compensated by a computer correction on the final display .

If a microscopical investigation is considered, the image field will be smaller : 250 µm would correspond to a lateral resolution 0.5 µm / pixel which could be considered as a satisfying outer limit . This is achieved with a microscope objective X40 on the camera. The immediate consequence is a camera focus depth some 10 µm wide. Of course the beam diameter has to match this dimension in order to remove "ghosts" of remote scatterers from the image. Such a reduction involves a more convergent laser beam and strongly limits the distance of maximum exploration see Fig.3- . Varying the beam focus and the camera objectives thus allows us to adjust the observation requirements between limits which become tighter as the magnification is higher. These optical constraints are in some way compensated by important advantages specific of these microscopical investigations :

i) the beam energy concentration is enhanced thus allowing us to reveal smaller scatterers
ii) the limited range of lateral exploration makes it possible to use vibrating beam or flat beam /8/ techniques instead of the stepper motors and a live image is obtained with remanent photocathod camera (N214) .
iii) the limited range of exploration corresponds to weak attenuation and no computer corrections are required .
iv) the reduced depth of focus allows us to locate the scatterers in depth with increased precision , in the micron range .

These new specifications of the experimental set up lead us to expect a more precise LST probing of interfaces and micro structures of epilayers .

3 - RESULTS

The origin of the scattering giving rise to the LST image in GaAs was related to condensed atoms on dislocations . It is likely that excess As atoms are concerned /30/ , especially in materials grown under As rich melt conditions ; these atoms were shown to precipitate and form small droplets some micron wide distributed along the path of the dislocations .

In Fig.4- we report investigations on a conventional LEC undoped material; the wafer comes from the central part of the ingot and the classical cell structure is observed at a macroscale (Fig.4a-) using a large laser beam (150 µm). Fig.4b-c- represent successive enlargements of windows indicated by white boxes; each view corresponds to an adapted thinner LST plane corresponding to a sharper focusing of the laser beam. Details of the walls become more precise to the point that small individual precipitates are resolved; they are crowded in the wall zone and arranged along curved lines entangled in the 3D space . Varying the vertical position of tomography allows verification that they effectively are point objects and not vertical string or rods .

The situation could be similar (Fig.5-) in InP crystals /31/,32/ but with a wider separation between the droplets; this should induce the illusion of non related defects. The density of defects strongly varies from sample to sample and in some cases inside the wafer itself. It is likely that the condensation mechanism of precipitates is very similar in InP and GaAs .

It is known that In doped GaAs materials show a reduced EPD density ; the corresponding LST images effectively reveal /22/ isolated ‹110› dislocations as shown in Fig.6- ; their correspondance with etch pits and also with X ray topography images can be satisfactorily verified /33/. A uniform cloud of microprecipitates is distributed in the bulk whereas a denuded zone (DZ) is surrounding the dislocation to a distance of some 50-200 µm apart . A graphical illustration of this situation is given in Fig.6b- These MP are presumably particles smaller than DP because the individual brightness is much lower and the density higher.

The only previous observation which can be related to these MP was performed by photoetching experiments /34/ /35/ and corresponds to a "micro roughness" of the etched surface ; we did not find evidence for these particles in the literature devoted to TEM analysis.
The collective effect of MP in the LST scattered intensity was discovered by Osaka /35/ and Moryia /36/; the high magnification of the microtomography allows us to resolve individual MP thus demonstrating

Fig.6c- that "speckle" artefacts as suggested by Osaka /35/ are not concerned in such images. Clouds of MP were observed in every GaAs-In samples we analysed and their density in the free space was estimated /32,35/ in the range 2.5 10^9 cm-3 which is a quite large value; then it is worth supposing that the size of these particles is rather small (› 1000 Å).

In ingot annealed materials a large cell structure is developed but the inner space of the cells is filled with MP as shown in Fig.7- ; three dimensional evaluation of the clouds was easily achieved revealing a sphere like arrangements selectively distributed; the local density of particles is in the range 3.5 10^9cm-3 which means that they are very small. Also a careful examination of the walls reveals a cloud of another kind of MPs which recovers and embodies the walls: these MPs are not easily observed because they superpose over the bright scatterers and ghosts of the walls which saturate the camera . It is to be supposed that the various cell MP (CMP) and the wall MP (WMP) are presumably of a different nature because they are differently distributed with respect to the cell structure; they seem to be specific of the manufacturer's fabrication process and likely of the high temperature annealing .

From all of these observations it turns out that LST is the more adapted technique for the study of microprecipitates and it is likely that their electronic influence on the GaAs IC specification could have been underestimated. The situation holds the same for Si where SiO_2 precipitates are clearly observed and numbered even at very low density.

We recently reached the experimental evidence that high magnification allows to obtain a more localised information consistent with the analysis of epilayers or micro circuits; an example is given in fig.8- showing the LST image of defects located in a 10 µm range beneath a test circuit on GaAs material; a wealth of work is now required to correlate the electrical specifications of the circuits with the presence of neighbouring defects.

Most of the investigations performed in the field of LST are devoted to GaAs bulk materials because there is a key problem of improving crystal growth technology; nevertheless this LST technique is as well available for InP as stated above but also for other materials such as CdTe or II-VI compounds such as ZnS , Zn Se /17/.

Surprisingly very few investigations (Ogawa /17/) were performed on Silicon may be owing to the established opinion that it is a well achieved and controled material. Si IC technology actually requires a precise control of the Oxygen concentration and of the gettering of metal impurity atoms by the Silicon dioxide precipitates . Our recent work showed that these particles can be easily observed by LST as observed in Fig.9-. This obviously means that Silicon will be a very promising field of research with LST inspection in the imediate future.

DISCUSSION AND CONCLUSION

Infra red imaging techniques of defects in III-V compounds was proposed some years ago by Ogawa /17/ and it was established that they can be compared to the traditionnal inspection techniques /33/ such as EPD or XRT . An important advantage is that they are perfectly non destructive , easy and fast to implement ; such inspection means must contributes in the data bases of wafer parametres already installed in some industries involved in the III-V ICs.

The LST method used for GaAs materials provide us with very good images of defect distribution . These images were found /22/ to agree fairly well with the dislocation pattern and assumed EL2 distribution. They were initially related to EL2 through different possible mechanisms of scattering; it now seems more realistic to directly interpret the LST image as a Rayleigh type scattering on microprecipitates of different metallurgical origins diversely arranged in the bulk depending on the local thermal situations .To our present knowledge there is not any evidence for LST observation of pure dislocations but only indirect evidence of decorated dislocations due to precipitates .

LST tomographes are currently used in Japan as systems dedicated to the GaAs wafer inspection at the laboratory level but also as "on line" non destructive test as well as surface etching or XRT controls . Presently two industrial instruments are developped in Japan and a second generation system is under development in France.

LST inspection of wafers leads to detailled and highly contrasted images of decorated dislocations and microprecipitates which can be possibly extended to a 3D information. It allows a very accurate evaluation of defects at a macroscopic as well as microcopic scale; extension of the method is expected to investigate interfaces or epilayer structures . LST also allows to obtain 3 dimensional information of the defect organization by accumulation of parallel tomographic planes ; some years ago japanese workers made some 3D mocke-up /38/ which clearly reveal the "sponge" texture of the intricated cells of dislocations.

It is likely that this imaging technique will be eventually used on various kind of semiconductors as a non destructive means of investigating microprecipitates.

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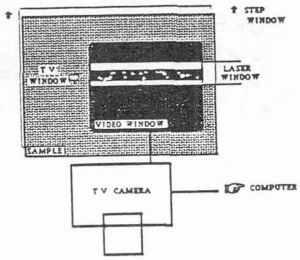


Figure 1- Organization of the LST experiment.

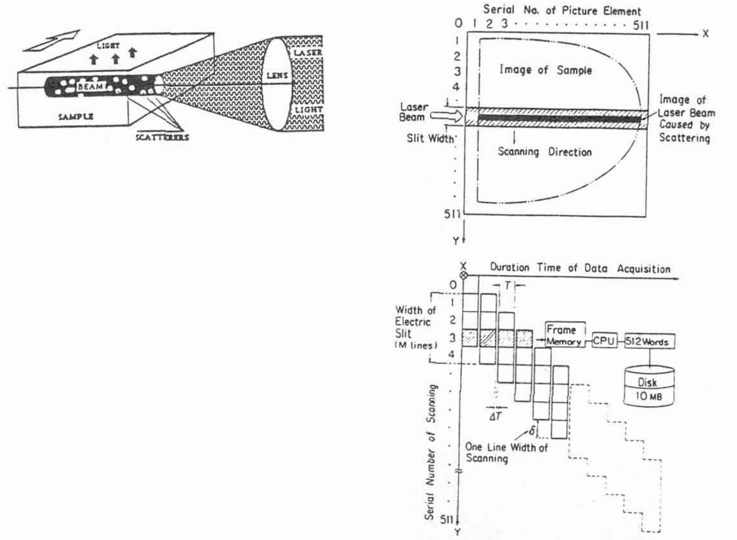


Image processing system of infrared light scattering tomography.
M: slit width of electric streak camera is chosen as 10 lines here, while $M=4$ in this figure for simplicity.
T: integration time at a given position of the laser beam, which is chosen as duration time of two TV picture frames and $N=2$ in this case.
ΔT: time of driving the laser beam by one scanning space and of storing the data integrated by the computer for 512 picture elements on one scanning line into the disk as the 512 words.

Figure 2- Image processing system of LST after Moriya /9/ .

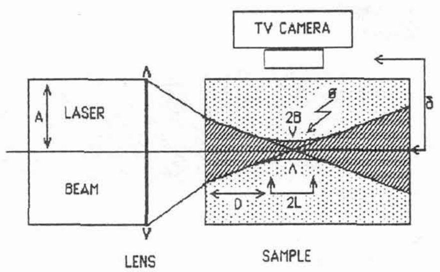
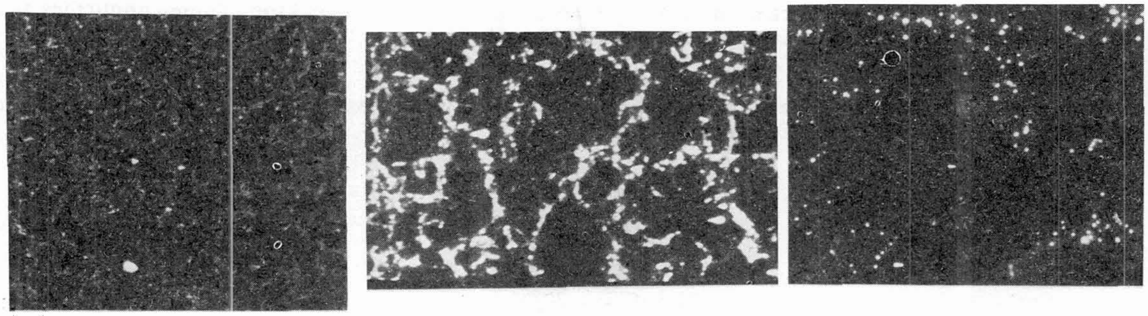


Figure 3- Beam focalisation in the sample .



-a- -b- -c-

Figure 4- LST images of defects in a GaAs conventional sample at different magnification (a - b - c).

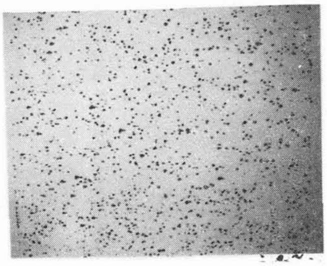
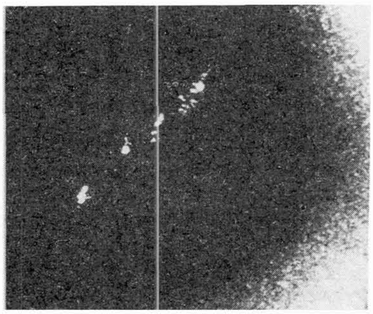
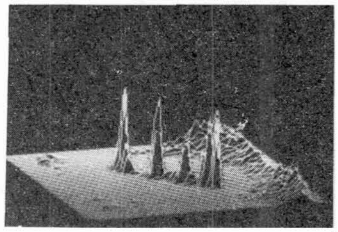


Figure 5- LST Tomography of InP material showing the distribution of microprecipitates

-a-



-b-



-c-

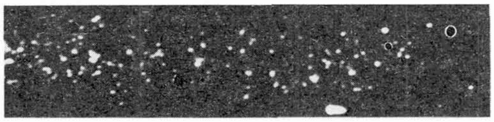


Figure 6- Indium doped GaAs : tomography of individual <001> dislocations(a) ; graphical illustration ; enlarged tomography of microprecipitates in the matrix (c) .

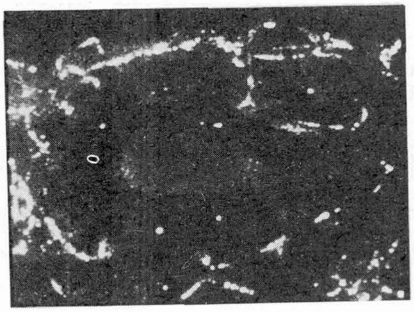
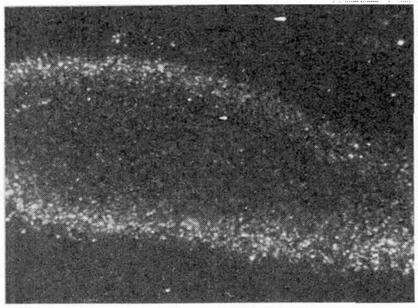
-a-  -b- 

Figure 7- Ingot annealed GaAs (a) and enlarged tomography of microprecipitates located in the cells (b)

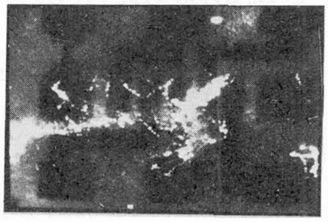


Figure 8- Defects in the vicinity of a GaAs circuit

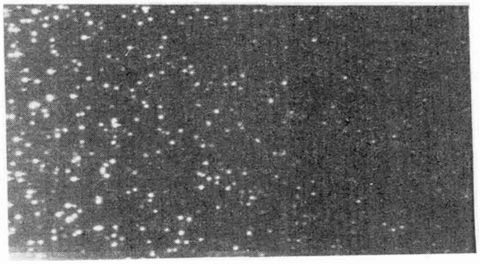


Figure 9- Silicon dioxide precipitates in Si materials.

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