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GaAs 웨이퍼의 적외선 영상기법 및 콘트라스트 반전 영상에 대한 새로운 해석

강성준*

Infrared Imaging and a New Interpretation on the Reverse Contrast Images in GaAs Wafer

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요 약

IC 기판의 가장 중요한 성질들의 하나는 넓은 영역에 걸쳐 균일해야만 한다는 것이다. 웨이퍼 결함 분석의 다양한 물리적 접근 방법 중에서 적외선 조사 기법에 특별한 관심이 모아지고 있다. 특히, 높은 공간적 분해력을 가지고 있는 근적외선 흡수 방법은 반-절연 GaAs 내의 결함들을 직접적으로 관찰하는데 이용되고 있다. 적외선 전송에 기초를 둔 이 기법은 신속하고 비파괴 적이다. 이 방법은, 직접적으로 GaAs 반도체의 적외선 영상은 결함의 광흡수 작용에 기인한 것임을 밝히고 있다. 반-절연 GaAs 내의 EL2에 관련된, 비 균일 적으로 분포된 결함들의 적외선 흡수 영상에서 콘트라스트가 반전되는 현상에 대해 새로운 모델을 제시하고 있다. 저온 포토퀀칭 실험은, 직접적인 방법으로, GaAs 웨이퍼의 콘트라스트 반전 영상은 밴드갭의 지엽적인 변동이나 전하 재분포에 의한 것이 아니라 흡수와 산란의 두 메커니즘에 의한 것임을 증명하고 있다.

ABSTRACT

One of the most important properties of the IC substrate is that it should be uniform over large areas. Among the various physical approaches of wafer defect characterization, special attention is to be payed to the infrared techniques of inspection. In particular, a high spatial resolution, near infrared absorption method has been adopted to directly observe defects in semi-insulating GaAs. This technique, which relies on the mapping of infrared transmission, is both rapid and non-destructive. This method demonstrates in a direct way that the infrared images of GaAs crystals arise from defect absorption process. A new interpretation is presented for the observed reversal of contrast in the infrared absorption of nonuniformly distributed deep centers, related to EL2, in semi-insulating GaAs. The low temperature photoquenching experiment has demonstrated in a direct way that the contrast inverse images of GaAs wafers arise from both absorption and scattering mechanisms rather than charge re-distribution or local variation of bandgap.

키워드 : GaAs 웨이퍼, 균질성 분석, 적외선 영상 기법, 콘트라스트 반전 영상, 반전 영상 해석

Key word : GaAs wafer, wafer homogeneity characterization, infrared imaging, reverse contrast images, new model of reverse contrast

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Ⅰ. INTRODUCTION

Semi-insulating GaAs (S.I. GaAs) is an important material for many applications. Czochralski growth of such high-resistivity material can be achieved without deliberate doping by the technique of liquid encapsulation(LEC). It is known that compound semiconductors such as GaAs 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 regime. These defects diversely affect the behavior of the elaborated circuits and leads to a scattering in the specifications [1]. 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 wafer surface :

- Chemical etching allows counting the etch pits (EPD) related to dislocations and to some extent to reveal chemical impurities .
- X-ray topography gives a detailed image of dislocations and striations. This experiment is, however, delicate and restricted to a thin layer of material.
- Photoluminescence leads to defect images from a region close to the surface.
- Other techniques such as electrical or electro-magnetic measurements are also available with a poor resolution.

A particular emphasis is to be put on the very simple techniques of infrared transmission(IRT) or laser scanning tomography(LST) because they are perfectly nondestructive, easy and fast to implement and scale adjustable [2, 3]. They also could be more easily related to physical causes as long as these optical phenomenon are carefully and unbiasedly interpreted.

In this paper we intend to comment the present state of the art in these two complementary domains of defect imaging especially dedicated to GaAs wafer inspection. Of cause GaAs is not the only material amenable to such investigation methods : InP, GaP, CdTe or even Si itself gives rise to unexpected features of hidden flaws.

First we will recall the main conclusions and the explanations on the possible origins of the IRT images; in a second step we will introduce the LST imaging method which is relatively recent and not widely known in Korea.

Ⅱ. Infrared Transmission Images

From the pioneering work of the British team [4] in the early eighties, it was known that a defect related pattern was observed in GaAs thick slabs when illuminated with infrared light in the wavelength range of 1 μm. The pattern was made of several typical shapes such as “cells”, “sheets’ and “streamers”. An example of the cell structure is given in Fig.1 which shows that the contrast in the image due to individual flaws is rather poor thus requiring image processing to be used. The box in Fig. 1 shows the contrast enhanced image after image processing.

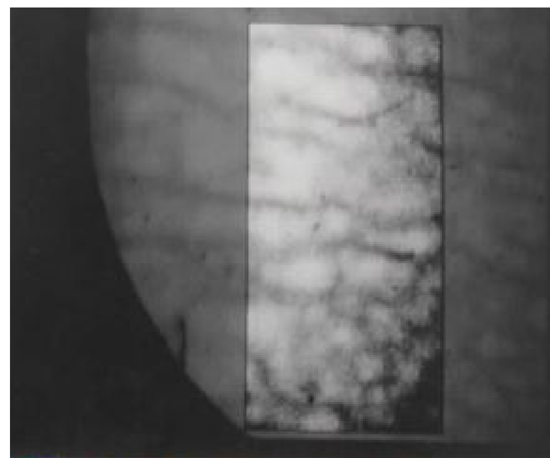


Fig. 1 Infrared transmission images (IRT) of a thin ($\sim 300\mu m$) slab of GaAs LEC undoped ingot. Box corresponds to image processed area [7].

From this initial work it also appeared that the cell structure was a dominant organization, especially when

dealing with LEC grown undoped semi-insulating materials. The size of the cell varies with growing parameters but also changes from seed to tail; standard dimension is in range 200 μm. It is undoubtedly related to the dislocation distribution.

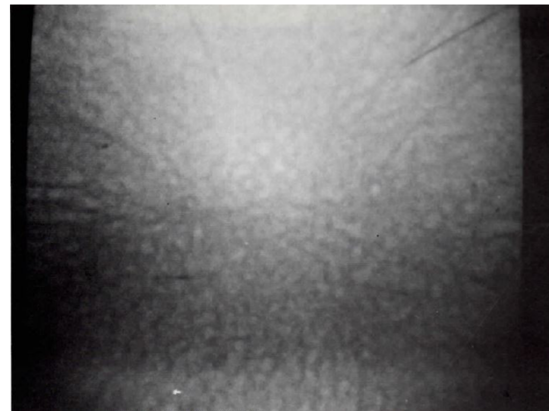
The cell structure was also observed by using stereo views and a discussion was opened on the 3D distribution of the cells [5]; it is now established that the walls of the cells are statistically oriented along (100) and (110) planes which correspond to an octagonal organization in the volume and not column type cylinders neither spheres.

Nevertheless these IRT images look fuzzy and have a poor contrast thus preventing direct examination of thin standard wafers (300 μm thick). Strong improvements were brought about by the use of numerical processing of such images ; IRT images from standard samples 300 μm thick are now available.

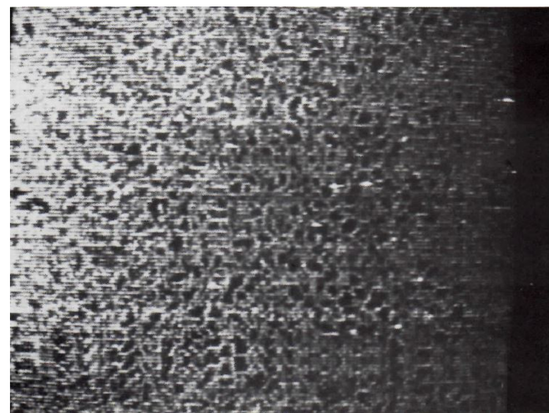
The key question about IRT images is of course to identify the physical origin of the optical image: a widely admitted explanation relies on the quantum absorption by the neutral $EL2^0$ centers which is known to occur at 1.1μm. Nevertheless $EL2^0$ is not the only possible optical mechanism and some attempts were made to introduce a low temperature photoquenching (PQ) transformation in the IRT images [6].

On a macroscale it was observed that the wafer becomes transparent and the fourfold figure of the background transmission disappears; This strong increase of transmission leads people to the illusion that the dislocation related pattern also vanishes thus demonstrating that dislocations are regions of high EL2 concentrations. Actually a more careful experiment showed that the pattern contrast is not affected by PQ at 77 K.

In Fig.2, we report a typical PQ result obtained on a classical LEC grown undoped sample. In this figure we can see that the cell pattern is clearly not affected by PQ whereas the background level of transmitted light is largely enhanced. This shows that dislocation must not be considered as main sources of EL2 centers. As a comparison, the same sample area was also observed by laser scanning tomography(LST) [7]. The fair agreement between these images leads to the opinion that light scattering could play an important role in the IRT image formation.



(a)



(b)

Fig. 2 Comparison of an IRT image (a) with LST image (b) on a same sample GaAs [7].

IRT images then are easy to achieve and it makes it possible to correlate the defects with the specifications of the FETs either by one to one comparison or by a general evaluation of the disorder in the wafer [8].

Ⅲ. Reversal of Contrast in IRT Image

It has been shown that high temperature annealing of undoped, semi-insulating crystals leads to a uniform EL2 distribution so that infrared imaging provides no information on dislocation non-uniformity. In such case, it is shown that near band edge "reverse contrast" images provide a very sensitive, optical technique for displaying inhomogeneities in annealed wafers of production thickness. Near band edge "reverse contrast" images were first reported by British team in low temperature photoquenching experiments 3 mm thick, undoped, LEC crystals [9]. The team found that the reverse contrast images were only observed following EL2 quenching at temperatures below 120 K. However, it is shown in later works that reverse contrast images can be observed in thin wafers (500 μm or less) without EL2 photoquenching [6, 10]. In Fig. 3a, b infrared images at wavelengths 1.0μm and 0.83 μm for a 300 μm, annealed, semi-insulating, undoped crystal at 80K are shown. The 1μm EL2 image is uniform and contains no information regarding the non-uniformities in dislocation density. By contrast, the near band edge image of Fig. 3b at 0.83 μm (1.49 eV) exhibits very detailed "reverse contrast" structure [6].

These direct observations have not as yet been satisfactorily interpreted. The British team who found the reverse contrast feature firstly suggests explanations of the reversed contrast by (i) some influence of mechanical strains from the dislocations or (ii) the presence of an unidentified shallow center which is spatially anticorrelated with EL2; also, (iii) possible influence of alterations of band tailing near the dislocations has been supposed. Later, an alternative interpretation based on carrier removal was proposed by German institute and its basic is depicted in Fig. 4 [11].

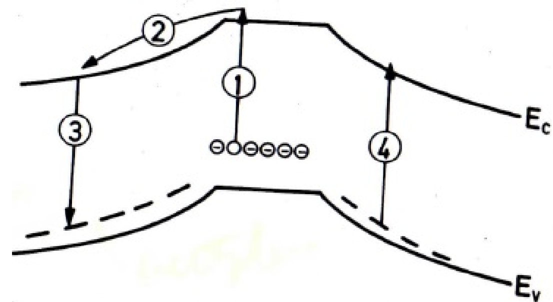
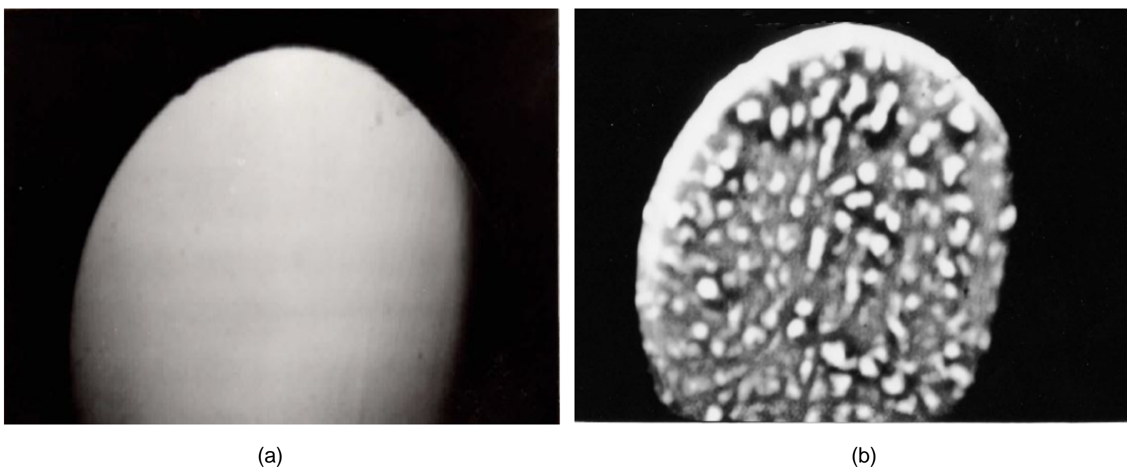


Fig. 4 Queisser's model to explain contrast and its reversal.



(a) (b)

Fig. 3 Infrared image of 300 μm thick annealed wafer of S.I. undoped GaAs at 80K and 1 μm (a), and 0.83 μm (b). The image at 1 μm is uniform because [EL2] non-uniformities have been removed by the annealing procedure. The near band edge image in (b) shows very detailed reverse contrast structure.

In Fig. 4 arrow 1 indicates photoexcitation of an electron out of one deep trap within a cluster traps. Arrow 2 shows the spatial carrier removal by the built-in field of the potential fluctuation created by the clustering of the deep traps. Arrow 3 symbolizes the capture of the removed photogenerated electron by a hole at a shallow acceptor. Steps 1 to 3 explain the quenching of the absorption 1 by electron attrition. Arrow 4 signifies the optical absorption involving the neutral acceptor which leads to the reversed contrast when near-gap illumination is used. However, it is found that the Qeisser's model is not satisfactorily explained the reverse contrasted mechanism because of that reverse contrast images can be obtained without EL2 photoquenching.

Ⅳ. New analysis of the contrast inversion

We have demonstrated that the inverse contrast is not directly related to EL2 photoquenching but preexisted, in fact, in the wafer before photoquenching and can directly be observed in the annealed sample. The inverse contrasted feature is occurred in the region very closed to bandgap (< 20 meV).

The elimination of EL2 absorption by photo-quenching :

i) increase uniformly the transparence of GaAs till the gap edge, it allows to a better observation of wafer structures.

ii) eliminates the positive contrasted component due to EL2 which reveals the negative structure.

We could imagine that the elimination of EL2 absorption is not directly related to EL2 itself; The negative structure is limited in the region (100 meV) immediately under the gap. The spectral transmission in that energy level shows an monotone decrease that it can attribute to the transitions of the localized energy levels (donors or acceptors).

We remark that the observation of an contrast situated in the given wavelength band requires an adequate sample thickness. Let $I(\lambda) = I_0 \exp - \alpha(\lambda) x$: Intensity traversing an semiconductor plate of thickness x for wavelength λ. The observed contrast is defined by an modulation $\Delta\alpha(\lambda)$ of the absorption coefficient, $\Delta\alpha = \alpha_1 - \alpha_2$ for the scheme in Fig 5.

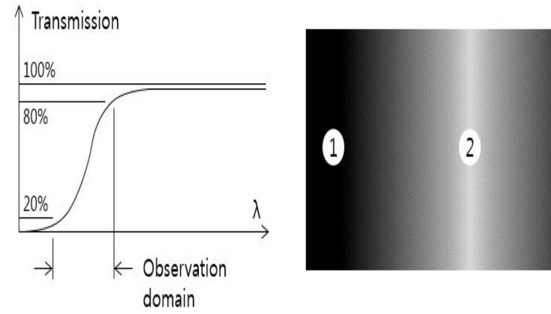


Fig. 5 Schema for the derivation of the condition giving the best observability of the contrast.

The modulation $\Delta I(\lambda)$ can be written as

$$\Delta I = - I_0 x \left[\exp - \alpha(\lambda) x\right] \Delta\alpha(\lambda)$$
$$= - I(\lambda)\, x\, \Delta\alpha(\lambda) \qquad (1)$$

So the optimum $\frac{d\Delta I}{dx} = 0$ corresponds to

$$- I_0 \left[\exp - \alpha(\lambda) x\right] \Delta\alpha(\lambda) + I_0\, x\, \alpha(\lambda) \left[\exp - \alpha(\lambda) x\right] \Delta\alpha(\lambda) = 0.$$

Then $x = \frac{1}{\alpha(\lambda)}$,

This condition corresponds to the best observability of the contrast and leads correlatively to an output intensity

$$I(\lambda) = \frac{I_0}{e} \qquad (2)$$

Then it follows that the optical spectrum edge (20-80% transmission domain) is the wavelength range for the best observation of the contrast and thickness x has to be chosen accordingly: the larger the thickness the larger the wavelength range for the observation window.

It is known that α increases monotonously with approaching the gap [12]. Then the measurements near the gap should be made on the thin samples (350 μm) while the measurement far away from the gap (until 100 meV) is made on thick sample (5 mm). The first situation has been investigated by our team [6, 12] : We have observed the negative contrasted structures at about 20 – 30 meV for the relative contrast value on order of 15 – 20%. In this zone, we have not observed the resolved spectral structure but a regular increase of α toward the gap limit.

The relative contrast between an dark zone 1 and an bright zone 2 (supposing that the two zones are homogeneous) is defined by:

$$C = \frac{T_1 - T_2}{T_1 + T_2} \quad (3)$$

with $\alpha_1 > \alpha_2$ as indicated the above Fig. 5.

Therefore,

$$C = \frac{\exp - \alpha_1 d - \exp - \alpha_2 d}{\exp - \alpha_1 d + \exp - \alpha_2 d} \quad (4)$$

or

$$C = \frac{1 - \exp\beta d}{1 + \exp\beta d} \quad (5)$$

with $\beta = \alpha_1 - \alpha_2 > 0$; in general $\beta \ll \alpha$.

C increases monotonously from 0 to 1 when the thickness becomes increased. And also C is independent on the illumination and the camera's spectral sensitivities. It is preferable to have a comfortable observation conditions in order to obtain the measurements directly and quantitatively. The sample is thick (5 mm), so the energy range will be more away from the gap than the previous works (upper limit 100 meV instead of 40).

However we remark that the cell structure results from a volume distribution, more or less random, of a fuzzy structure. Therefore the distinction criterion "wall", "cell" which defines the contrast must be used cautiously. The final image resolution mainly depends on the object itself. The average dimension of a cell is of 200 to 500 μm, that is, a sample of 350 μm thickness permits reasonably to define the real "cells" and "walls", while we will inevitably have a certain mixing of two categories in 5 mm sample.

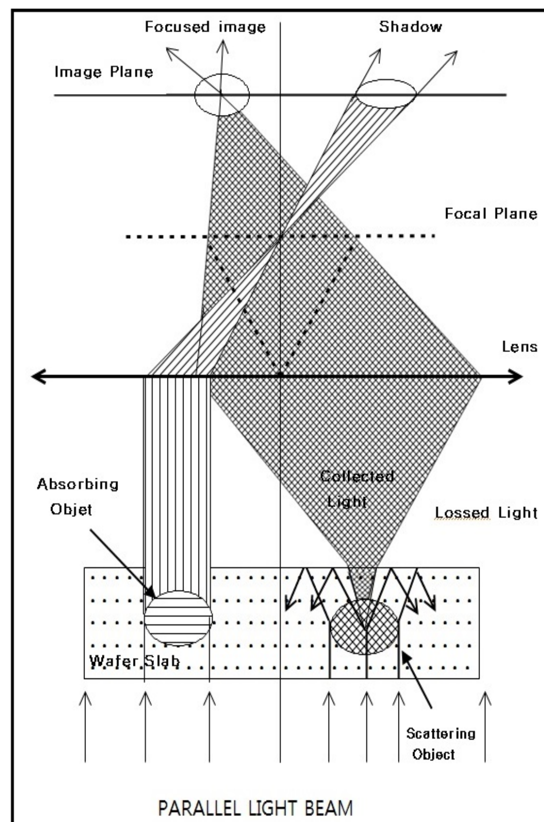


Fig. 6 Model to explain contrast and its reversal.

In general an image observed in positive contrast as well as in negative contrast is not simply a shadow projection of an absorbing object. The image formation by the lens needs focalization conditions [12]. That is, we have to deal with the lights scattered as much as absorbed(Fig. 6). This diffusion may occur either by wave diffraction on the local electronic resonances or by graded index and phase variation. Because of the very strong refraction index of GaAs, the solid angle useful for the diffused and collected light, is very small so it can expect that the light-diffusing objects can give a very good contrast in transmission due to the strong "loss of light".

It was shown that indeed a proportion of non-negligible light is diffused but this phenomenon is limited to the Rayleigh scattering on the microprecipitates which decorate dislocations and gives rise to the observations of tomography LST [8]. The gradients of index, as Skolnick [9] has urged, may not participate in image; our experience confirms exactly this point of view. The “images” of cells linked to EL2 are sufficiently fuzzy to that we can assign them mainly to the absorption in view of the fact that the non parallelism rigorous of incident light rays also entails an effect not negligible for focusing.

Ⅴ. CONCLUSIONS

The infrared imaging method is one of the import techniques which demonstrated directly the types of inhomogeneity present in LEC GaAs. Study of near band edge infrared images at low temperature has been demonstrated to be a very sensitive method for the investigation of the uniformity of annealed wafers. An alternative model based on both light diffusing objects and absorbing species is presented, the former can give a very good contrast in transmission due to the strong "loss of light".

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