APPLICATION OF ELASTIC MID-IR-LASER-LIGHT SCATTERING FOR NON-DESTRUCTIVE INSPECTION IN MICROELECTRONICS

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ABSTRACT

Some possible applications of the low-angle mid-IR-light scattering technique and some recently developed on its basis methods for non-destructive inspection and investigation of semiconductor materials and structures are discussed in the paper. The conclusion is made that the techniques in question might be very useful for solving a large number of problems regarding defect investigations and quality monitoring both in research laboratories and the industry of microelectronics.

INTRODUCTION

Over 15 years, the method of low-angle mid-IR-light scattering (LALS) have been actively used by us for investigation of the large-scale electrically-active defect accumulations (LSDAs) in semiconductors (see e.g. Refs.[1–15] and references cited therein). We shall consider below some possible applications of LALS and techniques recently developed on its basis for solving some specific problems of material and structure testing in microelectronics.

BRIEF DESCRIPTION

For the beginning let us briefly remind the basic principles of LALS. This method is founded on elastic scattering of IR light by inhomogeneities of semiconductor crystals — like the method of laser tomography,— but in LALS, as distinct from the laser tomography, the scattering at relatively low angles is registered — from about 2° to less than 15° in crystal — and light with large wavelength is used as a probe emission — routinely the radiation of CO_2- or CO-lasers with the wavelength of 10.6 μm and 5.4 μm, respectively, is applied. Application of mid-IR-light makes the technique sensitive to the presence of domains with enhanced concentration of free carrier or changed conductance type (FCAs) and measuring in the above interval of angles allows one to observe defects with the sizes from several microns to several dozens of microns.[1,2,9,11] (Writing FCAs we mean both manmade domains with changed carrier concentration or conductance type — e.g. doped domains of semiconductor structures — and natural LSDAs which always are FCAs.)

A number of procedures has been developed, which enable the distinguishing of the scattering by FCAs from that by different defects. These procedures consist in the investigation of the light scattering with different wavelengths or measuring the dependencies of the light scattering intensity on sample temperature.[9,12,14,15] In addition, the latter procedure and the investigation of the influence of photoexcitation on light scattering intensity allows one to

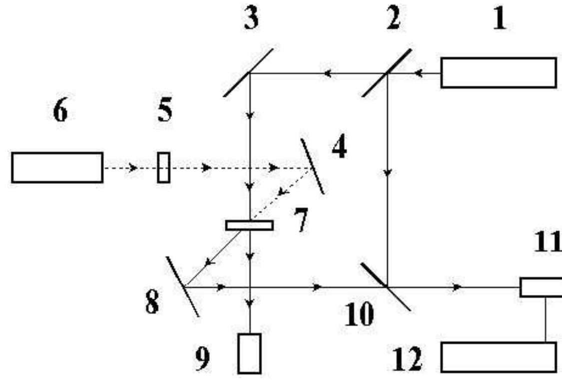

Figure 1: Optical diagram of angle-resolved LALS: (1) mid-IR-laser; (2,10) semitransparent mirrors; (3,4) mirrors; (5) filters; (6) exciting laser (used in LALS with photoexcitation); (7) sample; (8) movable mirror; (9,11) photoreceivers; (12) computer.

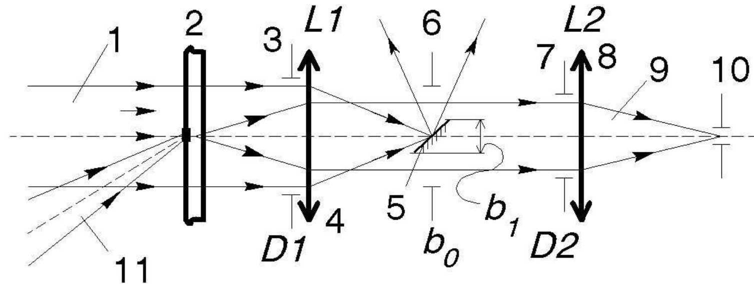

Figure 2: Optical diagram of the SLALS microscope: (1) mid-IR probe wave; (2) sample; (3,6,7) diaphragms; (4,8) lenses; (5) mirror or opaque screen; (9) scattered wave; (10) IR photodetector; (11) exciting light beam (used in OLALS).

determine thermal and optical activation energies of point centers in LSDAs.[9,12] Moreover, LALS allows one to investigate large-scale recombination-active defects (LSRDs) and large-scale gluing centers (LSGCs) discriminating between those in near-surface layers — including epilayers — and those in substrate bulk: the former are studied by use of the surface optical excitation,[16] while the latter are observed using the volume photoexcitation.[1,8,10] (Typical examples of LSRDs are such defects as grain boundaries, dislocations, swirls, precipitates, their clusters and aggregations of recombination point centers.)

Presently, the two following schemes of LALS are developed. One of them — the conventional LALS or LALS with angular resolution — registers light scattered by all defects which are situated within the probe beam,[2,10,12] see Fig.1. In the other — in scanning LALS microscopy or SLALS, which is a kind of the scanning laser microscopy,— every singular defects are visualized,[17−20] see Fig.2. By combining these two schemes, one can determine concentration of defects, their spatial distribution, and hence, one can estimate the value of deviation of their dielectric constants from those of crystal bulk outside them $\Delta\epsilon$ (in the case of FCAs — and, as mentioned above, LSDAs always are FCAs,— the concentrations of free carriers in them, Δn, can be evaluated).[9,10,14,15]

The LALS technique is of high sensitivity, it allows one to observe defects with the vari-

ation of dielectric constant $\Delta\epsilon$ down to 10^{-5}–10^{-4} — i.e. with Δn down to 10^{13} cm^{-3}. LALS is non-destructive and contactless, it has no limitations on the tested wafer diameter.

INDUSTRIAL AND LABORATORY APPLICATIONS

Let us dwell on some possible specific applications of LALS as the checking technique in the field of the industrial microelectronics.

Inspection of semiconductor wafer homogeneity

As mentioned above, LALS enables the observation of LSDAs with the sizes from several μm to several tens μm with point detect concentration in each of them down to 10^{13} cm^{-3}. This method permits the investigation of the LSDA composition and the influence of various thermal treatments and operations of an industrial technological cycle on them. Wafer mapping is possible by means of SLALS. Incoming control with posterior utilization of substrates in the production process and technological step checking by using free chips are also possible.

These techniques are well developed now and a prototype of the instrument is available.

Fig.3 demonstrates the images of LSDAs in different bulk semiconductors obtained with the SLALS microscope (1×1 mm^2 areas are presented). The microphotographs of LEC undoped InP (a), LEC InP:Fe (b), LEC SI GaAs annealed at 900°C in a sealed quartz ampule when produced (c), CZ Si:B with high (d) and low (e) epd, and CZ Si:B coated with 1200 Å thick SiO_2 layer (f) are presented. White spots are the images of LSDAs. One can find more details on these pictures in Refs.[18-21].

The disadvantage of LALS (and SLALS) is its inability to discriminate between LSDAs situated in crystal bulk and ones located in near-surface layer. To remove this shortcoming, LALS tomography with longitudinal resolution down to 10–20 μm is now under development on the basis of SLALS. The solution of the problem does not seem to meet any difficulties. Its successful solving would enable the testing of homogeneity of "working" near-surface layers of wafers and epitaxial layers. Note that layer inspection is possible even if it is under coating or under other layer — up to the stage of metallization. For instance, the homogeneity of a silicon wafer under oxide layer may be checked — Fig.3(d) — as well as its near-surface layer .

Inspection of presence of LARDs in near-surface, near-interface and epitaxial layers

The methods of optical beam induced LALS (OLALS) and LALS with optical pumping,[16] which may be used for such inspections, are the optical analogs of such well-known methods as EBIC and OBIC, yet they require neither Shottky barrier or $p-n$ junction nor complicated sample preparation. Like in the above case, a significant advantage of these techniques is their ability to test multilayer structures including layers covered with other layers. Also there are no limitations on sample size and resistivity in LALS. So wafer mapping, all-round incoming and step control with subsequent utilization of substrates in production cycle are possible.

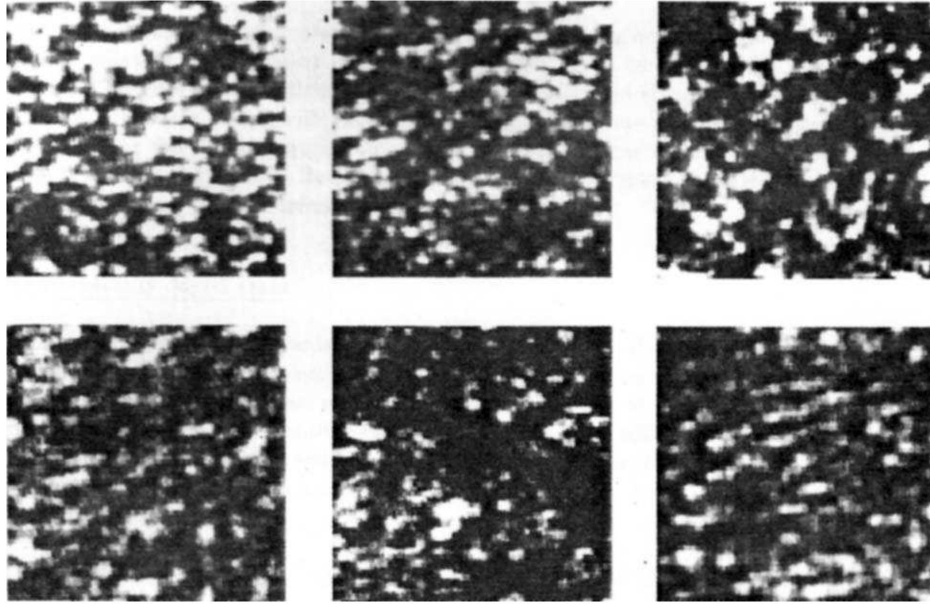

Figure 3: SLALS images of LSDAs in semiconducting wafers; the first row (left to right): undoped LEC InP (*a*); LEC InP:Fe (*b*); LEC SI GaAs annealed at 900°C (*c*); the second row (left to right): CZ Si:B, $\rho=12\ \Omega\,\mathrm{cm}$, high epd (*d*); CZ Si:B, $\rho=12\ \Omega\,\mathrm{cm}$, low epd (*e*); CZ Si:B (different establishment) under 1200 Å thick SiO_2 layer (*f*); 1×1 mm^2 , λ_{sc}= 10.6 μm. Amplification factors are equal in the following pairs of pictures: (*a*) and (*b*), (*d*) and (*e*). White spots in the photographs are the images of LSDAs.

Control of LSRDs in the substrate volume, including tomography, is also possible, but this is likely of interest for the production of γ-ray detectors, whose resolution is determined by LSDAs and LSRDs,[10] various nuclear-ray counters, volume photodetectors, *etc.*

As of now, a cycle of experiments has been carried out, which have shown the possibilities of these methods.[8,10,16,19,20]

Fig.4 demonstrates the microphotographs of near-surface regions of Si wafers subjected to different polishing and oxidation procedures (1×1 mm^2 areas are presented). The images of FZ Si:P wafers after chemico-dinamic (*a*) and mechanical (*b*) polishing procedures, and the image of CZ Si:B wafer coated with 1200 Å thick SiO_2 layer (*c*) are given in this figure. The darker image, the shorter non-equilibrium carrier effective lifetime is. The focused 633-nm-wavelength radiation of 55-mW He-Ne laser was used in this experiment for electron-hope pairs photoexcitation in near-surface layers (see Fig.2).

Testing of specially doped areas

LALS may be also used for the inspection of such parameters of specially doped domains of semiconductor structures as their sizes, concentration of free carrier in them and surface resistance. The inspection of these parameters is also possible even after different layers are grown and coatings are given (until metallized). The domains with the sizes greater than 1 μm and the variation of free carrier concentration greater than 10^{13} cm^{-3} can be tested. Nowadays, the development of a prototype of such instrument is being in the final stage.

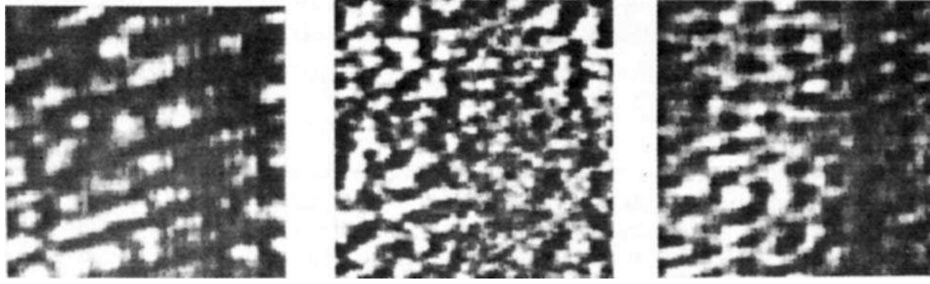

Figure 4: OLALS microphotographs of Si wafers, defects in near-surface layers (left to right): FZ Si:P, chemico-dinamic polishing (a); FZ Si:P, mechanical polishing (b); CZ Si:B under 1200 Å thick SiO_2 layer (c) — the same region as that given in Fig.3(f); 1×1 mm^2 , λ_{sc}= 10.6 μm, λ_{ex}= 633 nm. Amplification factor in picture (b) is by 100 times greater than in picture (a), and that in picture (c) is by 10 times greater than in picture (a). The brighter image, the longer the non-equilibrium carrier effective lifetime is. The dark areas are the images of defective regions.

Inspection of gettering process efficiency

We would like to specially emphasize that the above techniques might be very useful for the inspection of the gettering processes efficiency.[22]

The presence of the gettering precipitates at the internal gettering process can be checked by OLALS or LALS with quasi-bulk photoexcitation. The presence and parameters of impurity atmospheres around the gettering precipitates can be checked by the conventional (angle-resolved) LALS and SLALS microscopy. The "working layer" may be tested by OLALS or LALS with surface photoexcitation.

The inspection of efficiency of the external gettering and gettering by implanted domains is also possible by the LALS-based techniques. The procedures proposed for these inspections are analogous to those described above for the internal gettering process.

CONCLUSION

So we can conclude that the LALS-based techniques might by a very effective non-destructive tool for solving a wide class of problems of materials and structures testing in modern microelectronics, which might be used both in laboratories and directly in the production cycle. We discussed only several most obvious possible applications of these techniques in this paper. We are sure, however, that they might find a great number of additional applications and be useful in many branches of microelectronics science and industry.

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