Optical Dark Field Imaging for Characterization of Semiconductors

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ABSTRACT

The principle of dark field imaging is comprehensively discussed using real images of dislocations, stacking faults and gettering phenomena due to defects obtained by Cz Si wafers and LEC semi-insulating GaAs crystals.

Resolution of dark field imaging is improved by Fourier transformation of Fraunhofer diffraction pattern obtained at an out-of-focusing position of an objective lens.

1. Introduction

Since dark field imaging due to optical systems is very important from non-contacting and non-destructive points of view for recognition of defects in semiconducting wafers and epitaxial layers, 90 degree scattering or light scattering tomography (LST), total internal reflection, surface scattering due to very large incident angle and Brewster angle illumination will be discussed here to characterize wafers and epitaxial layers of semiconductors such as LEC GaAs crystals and CZ Si wafers.

Fourier transformed imaging of light scattering tomographs (FT-LST) is discussed for resolution improvement of dark field imaging system.

2. Dipole Radiations as Elementary Processes in Optical Procedures [1]

Light amplitude in a transparent material is the total sum of radiations from all the dipoles induced by electric field of an incident optical beam and the beam itself.

The equation motion of an electron is given by

$$(1) \quad d^2x/dt^2 + \gamma dx/dt + \omega_o^2 x = (q/m)E_o e^{i\omega t},$$

where q, m, γ, ω_o, x and $m\omega_o^2 x$ are, respectively, the charge, mass, damping factor, resonating angular frequency, deviation from its averaged position under no electric field and restoring force of the given electron, and E_o and ω are, respectively, the local electric field on the electron and the angular frequency of the incident laser beam. Therefore, the induced dipole moment is given by

$$(2) \quad p = qx = (q^2/m)E_o e^{i\omega t}/[\omega_o^2 - \omega^2 + i(\gamma\omega)] = p_o e^{i\omega t}.$$

The radiation energy emitted from this dipole moment is proportional to $p_o^2\omega^4$, where p_o is the amplitude of the moment. The energy can be observed along direction perpendicular to the moment vector p but not along the direction parallel to p.

The phase of induced polarization is delayed by $\tan^{-1}[\gamma\omega/(\omega_o^2 - \omega^2)]$ from that of the applied electric field because of $\omega_o > \omega$ in visible to near infrared frequency range and then the light velocity in a material is slower than that in vacuum because of the summation of the delayed dipole radiation and the incident beam.

X-rays with wavelength such as 0.5 to 1.5 A which are usually used for x-ray structure analysis will polarize almost all the electrons included in materials because of $\omega_o < \omega$, and thus the refractive index is less than unity since $\tan^{-1}[\gamma\omega/(\omega_o^2 - \omega^2)]$ becomes to negative.

IR radiations of about 1,000 nm wavelength can polarize only electrons located at outermost orbits and/or traps due to dopants, impurities and/or defects because binding energy of the movable electrons mentioned above must be the same order of magnitude of the photon energy for illumination. Therefore, the optical characterization is more sensitive for electronic defects in crystals than that of X-rays, which is beneficial for characterization of semiconductors.

The total sum of amplitude f due to the dipole radiation is given by

$$(3) \quad f = \int_V \rho(r) e^{ikr} dv.$$

Here, $\rho(r)$ is the density that the polarizable electrons due to an incident beam within a volume element dv whose mid-point is defined by the radius vector r, k is the scattering vector defined by $(2\pi/\lambda)$ multiplication of the unit vector difference between the incident and the scattered beam direction and V is the volume illuminated by the beam.

If spatial distribution of the polarizable electrons is completely uniform or given by $\rho(r) = \rho_o$ (constant) within V, the equation (3) will have a finite only when $\Theta = 0$, where 2Θ is the angle between directions of the incident and the scattered light. This means that the incident light will straightforwardly pass through the optically uniform specimen without scattering.

When the density of electrons is not uniform or $\rho(r) = \rho_o + \Delta\rho(r)$, we will be able to detect the contribution due to $\Delta\rho(r)$ if the following integral is finite:

$$(4) \quad f = \int_V \Delta\rho(r) e^{ikr} dv.$$

This equation is equal to the summation of dipole radiations deviated from the incident beam direction, that is, this gives "light scattering". Therefore, every spatial inhomogeneity acts as a light scatterer, which will be caused by lattice defects, radiation damages due to ion implantation, doping inhomogeneity, small particles such as voids and impurity segregation and interstitial atoms and/or vacancies in crystals [1].

3. Results and Discussion

The optical arrangement to detect 90 degree scattering is known as Light Scattering Tomography (LST)[2] which is biased on ultra-microscopy. By layer-by-layer LST, three dimensional structures and distribution of defects in a crystals are analysed [3,4]. Thickness of denuded zone and size and position of the oxidation related defects such as precipitates and stacking faults (OSF) in Cz Si wafers are detected by LST [5]. Gettering action due to defects such as dislocations, oxygen precipitates and OSF were also confirmed by this method and by the total internal reflection. Dislocation lines, especially decorated by gettering of impurities and/or excess atoms, and inhomogeneous distribution of trapped electrons such as EL2 centers in GaAs crystals were detected by light scattering. A sort of resonance scattering was observed when ω becomes closer to ω_o, which is confirmed in GaAs crystals [6].

Spectra of the light scattered from wafers were measured by an optical frequency analyzer, by which inelastic components and photo-luminescence were clearly and separately observed [7].

A total internal reflection method is developed to detect very fine defects just under a mirror-polished surface of a CZ Si wafer, because only the light scattered by the defects will be observed through out the mirror surface, while the majority of the incident laser beam can not come out from the surface because of total reflection on it [8].

Fourier transformed imaging LST was developed to obtain shape of a scatterer which was usually imaged as a dot by correct focusing, because its size was smaller than resoluving power of a microscope used here. Since the Fraunhofer diffraction pattern caused by a defect to be studied is obtained by slight shift of an objective lens from its just focused position along its optical axis, the pattern is reconstructed into a shape of the defect by Fourier transformation [9]. Many shapes reconstructed by this method are very similar to the shapes observed by transmission electron microscopy (TEM).

Brewster angle illumination is used to observe the defects without cleaving samples because the p-component of an incident laser beam completely penetrates into a semiconductive wafer, even if its refractive index n is more than 2, where the Brewster angle is given by $\tan^{-1} n$.

The D-defects in a CZ Si wafer and misfit dislocations located between hetero-epitaxial layer of $Si_{0.92}Ge_{0.08}$ on a (001) Si wafer and its substrate were clearly observed by Brewster angle illumination of 820 nm radiation from a laser diode (LD)[10].

The s-component illuminated with very high incident angle does not enter into an objective lens because of the large incident angle, but scattered light will detected though the lens, which is caused by atomic and/or chemical compositional fluctuation, even if the surface was polished into a mirror surface. This dark field imaging is very effective to detect the constitutional inhomogeneity on epitaxial layers, especially multi-quantum layers.

4. Conclusion

Effectiveness and usefulness of optical dark field imaging on semiconductor characterization was analytically and experimentally confirmed here.

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