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CATHODOLUMINESCENCE STUDIES OF DISLOCATIONS IN SEMICONDUCTORS

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Abstract: The cathodoluminescence accessories of the scanning electron microscope for semiconductor examinations are described. Brief notions of spectroscopy are recalled. The dislocation contrasts are classified as "usual" (black dot, dot and halo) and "unusual" (no contrast, white contrast on monochromatic image). Examples of recent applications are given.

I - INTRODUCTION

Cathodoluminescence (CL) is an analytical tool of the scanning electron microscope (SEM) and of the scanning transmission electron microscope (STEM). The minority carrier lifetime, energy gap and other fundamental properties of semiconductors can be determined by use of this method with a spatial resolution of the order of 1 \mu m. In addition, crystal defects (precipitates, grain boundaries, dislocations) can be detected in the CL-mode. Now, it has been well established that in semiconductors, defects such as dislocations are harmful to the functioning of electronic and optical devices. Therefore, it can be easily understood why CL, which is non destructive, is such an attractive method of characterization. It has been widely developed in the last few years. In this review, some information concerning the different instrumental systems used for CL examination will be given, with the emphasis on the possibilities and performances of these systems. Then, the main recombination mechanisms will be presented. From the general theory of CL, an attempt will be made to draw some quantitative conclusions which will be useful in the last part, devoted to the CL studies of dislocations in semiconductors.

II - EXPERIMENTAL TECHNIQUE

The experimental technique has already been reviewed by Pfefferkorn et al [1] and Holt [2]. Only the main points of interest will be resumed below.

The first problem is detecting the light emitted by the specimen under electron bombardment. In figure 1, the energy band gaps $E_g$ of the main covalent, III-V and II-VI semiconductors, and their corresponding wavelengths are presented together. Indirect band gap materials are indexed with the subscript (1). For a few ternary compounds the band gap energy has been plotted as a function of the composition. The range of spectral response of detectors is indicated. Photomultipliers, with high gains and low noise amplification characteristics are best suited for wavelengths up to 1.2 \mu m. Beyond this limit, photovoltaic detectors must be used with all the inherent drawbacks to these detectors (noise, low amplification). However, the study of the luminescent emission at these wavelengths are of the greatest interest. They correspond to either band to band recombination for narrow-gap semiconductors (IR
detector application) or to the recombination corresponding to a fraction of the band gap when deep levels are involved. For instance very few CL studies have been presented on Cd Hg Te [3].

In order to achieve the highest possible sensitivity light collection may be improved by either the fitting of an ellipsoidal mirror which focuses the light on the detectors or by working in the transmission configuration (TCL) [4]. In the last experimental set-up, the CL generated at the surface is transmitted through the sample (\( \approx 300 \mu m \) in thickness) and detected by a detector situated just below the specimen. High collection efficiency is achieved by the small distance between the CL source and the detector.

Generally, grating monochromators have been used for spectral CL measurements and for monochromatic imaging [5], sometimes at wavelengths up to 3 \( \mu m \) [6]. The wavelength resolution is of the order of 1 nm. The spectrum can also be recorded simultaneously for all wavelengths (analogous to EDS in X-ray analysis) through the use of an optical multichannel analyser (OMA) described by Löhner et al [7]. Instead of a monochromator, an interferometer can be used [8]. The Fourier transform of the interferogram gives the optical spectrum. This method greatly improves the detection sensitivity especially in the IR region where the detector noise is the main limitation.

The beam blanking technique used in conjunction with a lock-in amplifier improves the signal to noise ratio and the image contrast [9]. In addition it permits the minority carrier lifetime measurements. Depending upon the different systems adopted,
one can distinguish the sequential (sampling) technique \([10][11][12]\), where the light is detected in a narrow time interval \(t, t + \Delta t\) (variable \(t\) is the time after the electron beam is switched off), and the simultaneous registration of the CL relaxation time: the single photon technique [8] applicable to materials with low CL efficiencies, and the streak camera technique [13][14] particularly useful for low lifetimes measurements (time resolution 100 ps).

Many installations are provided with a liquid helium stage so the specimen can be cooled down to 10\(^0\)K [2][8][9][11][14]. Many advantages are expected from CL studies at low temperature: the lines are usually brighter and sharper and therefore more significant.

Finally, it is worthwhile noticing that some TEM-STEMs are equipped with spectral detection and liquid helium stage [15][16]. Some dedicated STEMs are also provided with CL detection [14] which allows CL imaging with a spatial resolution in the order of 100 nm with thin specimens.

### III - SPECTROSCOPY

The CL emission is usually devided into intrinsic and extrinsic effects. Intrinsic effects are related to the semiconductor itself and include band to band recombination and free exciton recombination. These transitions are not efficient in indirect gap semiconductors as they require the contribution of a phonon to conserve momentum.

For band to band recombination, the wavelength is such that \(h\nu = E_g\) and for free exciton recombination (EX) we have

\[
h\nu = E_g - E_{ex}
\]

\(E_{ex}\) is the exciton binding energy. In a hydrogenic model, \(E_{ex}\) can be expressed as

\[
E_{ex} = \frac{\mu e^4}{2\hbar^2 \varepsilon^2} \cdot \frac{1}{n^2} \quad \text{with} \quad \frac{1}{\mu} = \frac{1}{m_e^*} + \frac{1}{m_h^*}
\]

\(\varepsilon\) is the dielectric constant, \(m_e^*\) and \(m_h^*\) the electron and hole effective mass respectively.

Extrinsic effects are relative to the defects present in the semiconductor which produce localized states in the forbidden band gap. They include band-level recombinations, pair transitions and bound exciton recombinations. In the first case, the photon energy of an electron-acceptor level (e\(A_0\)) or a donor level-hole (\(D_0h\)) recombination is given by

\[
h\nu = E_g - E_a \quad \text{(Ed)}\]

where \(E_a\) (\(E_d\)) is the acceptor (donor) binding energy, the thermal energy of free particles being neglected.

Pair transition (\(D_0A_0\)) between an electron trapped on a donor and a hole on an acceptor gives a photon of energy:

\[
h = E_g - (E_d + E_a) - \frac{e^2}{4\pi\varepsilon_r r} \quad [18][19][20]
\]

\(r\) is the donor-acceptor distance. The last term represents the coulombien energy.

In the case of a bound exciton which is generally localized by neutral species, the photon energy is

\[
h\nu = E_g - E_{ex} - E_b - (E_{15} - E_{ns})
\]

\(E_b\) is the exciton-impurity binding energy.

For instance, in the case of a bound exciton on a neutral acceptor (\(A_0X\)), the corresponding recombination lines are firstly \(AX\) (\(y\) is the chemical symbol of the acceptor) which is the most intense, where the acceptor is in its fundamental state \((E_{15})\) and secondly \(AX\) \((n > 1)\) where a part of the recombination energy is given to
the hole, leaving the acceptor in an excited state \((E_{NS}, \text{two hole transition})\). All these lines can have phonon replicas. The intensity of the \(n^{\text{th}}\) phonon replica \(I_n\) is given by
\[
I_n = I_0 \frac{N^n}{n!}
\]

\(I_0\) is the zeroth phonon line intensity and \(N\) the number of emitted phonons. \(N\) reflects the coupling of the defect with the lattice.

Recombination can occur at point defects such as vacancies, interstitials and/or impurity complexes. Sometimes, this interpretation can be misleading: in the case of ZnTe, two acceptor levels were attributed to the Zn vacancy. Later on, by use of CL and PL techniques it was demonstrated that these levels were in fact related to the presence of impurities such as Cu and Li \([21][22]\).

Not all transitions are radiative; non radiative recombination can occur by the Auger mechanism which transfers the recombination energy to an electron or a hole. As the level becomes deeper in the band gap the phonon coupling increases. Multiphonon recombination becomes more and more efficient and therefore less and less effective for radiative recombinations \([23][24]\). An example of a deep level radiative transition observed by photoluminescence is given by Mircea-Roussel and Makram-Ebeid \([25]\) concerning the mid-gap EL2 level in Ga As.

The band to band peak energy dependence on temperature must be the same as for the band gap, that is, for most semiconductors it must increase with decreasing temperature. Conversely, this effect can be used to measure the temperature of the specimen under the impact of the beam. Gatos et al \([26]\) used this effect to measure the temperature increase when the beam current was varied from 350 to 1150 nA on an InP specimen. An energy shift of 12 meV in the band to band line was noticed, corresponding to a temperature increase of approximately 40°C. In the same way, Davidson et al \([27]\) were able to measure locally the working temperature of a Gunn diode.

As long as the injection level is kept low, the peak heights exhibit a linear relationship with the beam current.

The most spectacular temperature effect is to induce large variations in the relative peak height and band broadening as the temperature increases. Only at low temperature can an accurate assessment of the origins of the levels involved in the recombinations be attempted. Recently, Chamonal et al \([28]\) showed that PL \((4°K)\) and CL \((15°K)\) spectra of CdTe doped by lithium diffusion are comparable. Due to its higher spatial resolution, the CL technique was able to demonstrate that a part of Li diffusion occurred by a grain boundary mechanism.

The effect of the dopant concentration on CL efficiency can be very important. Cusano \([29]\) measured the CL band edge efficiency in Ga As as a function of the doping concentration. In the case of Te doping, the CL efficiency rises by more than 3 orders of magnitude between 10^{16} and 10^{18} donors cm^{-3} and then decreases by two orders of magnitude to 10^{19} cm^{-3}. The maximum is reached at a concentration where the semiconductor is degenerate and before precipitation occurs. Similar effects were shown in Ga Sb : Te \([30]\). Wittry was able to correlate the CL efficiency with the local variation of Te concentration in Ga As by electron probe micro-analysis (EPMA) \([31]\). When the CL signal variation was very important, the corresponding EPMA signal variation was at the sensitivity limit of the method.

In the case of ternary alloys, the energy position of the band to band peak gives an approximate value of the concentration. In some cases, the variation of the intensity is more sensitive. In Ga_{x}Al_{1-x}As, a variation in \(x\) induces a variation in CL intensity as Ga As is a direct band gap semiconductor (CL efficient) and Al As is an indirect band gap semiconductor. This effect has been used by Levin and Ladany \([32]\) to reveal composition inhomogeneities in a Ga Al As film deposited on Ga As.
IV - DISLOCATION STUDIES

1 Introduction

CL dislocation contrast will be arbitrarily divided into "usual" and "unusual" contrasts. "Usual contrast" refers to the CL contrast which is most frequently encountered in semiconductors: the point of emergence of a dislocation almost perpendicular to the surface appears either as a "black dot" of a few microns in diameter or as a "dot and halo" which consists of a black dot surrounded by a region (\( \phi \sim 20\mu m \)) of CL intensity greater than the bulk one. "Unusual" contrast refers to dislocations exhibiting either a white contrast or no contrast at all.

Most of the time, the dislocations observed in the CL-mode have not been characterized by other methods. Nevertheless, correlations have been made with chemical etching \([33][34][35]\), X-ray topography \([36]\) and with TEM (see below).

Some applications of the CL dislocations observation will be given, including plastic deformation, interface defects; optical devices degradation and semi-insulating GaAs. CL and EBIC studies of dislocations in semiconductors have been reviewed by Booker \([37]\). Below some aspects of this paper will be resumed and some new results presented.

2 "Usual contrasts"

a) Black-dot contrast

The CL intensity \( I_B \) generated in a bulk material by a radiative recombination mechanism can be expressed as:

\[
I_B = \frac{G_i b}{e} \cdot \eta_r
\]

(1)

\( G \) is the generation factor of electron-hole pairs per incident electron, \( i_b \) the beam current and \( \eta_r \) the internal quantum efficiency for radiative recombination. \( \eta_r \) is the ratio of the radiative recombination rate to the recombination rate by all mechanisms (radiative or not). Therefore

\[
I_B = \frac{G_i b}{e} \cdot \frac{\tau}{\tau_r}
\]

(2)

\( \tau_r \) is the radiative recombination lifetime and \( \tau \) the effective lifetime for radiative and non-radiative recombination. If \( \tau_{nr} \) is the non-radiative lifetime, then

\[
\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}
\]

(3)

In a dislocation, if we assume that a new non-radiative mechanism operates with a lifetime \( \tau_D \), then the CL intensity generated at the dislocation will be:

\[
I_D = \frac{G_i b}{e} \cdot \frac{\tau'}{\tau_r}
\]

(4)

with

\[
\frac{1}{\tau'} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} + \frac{1}{\tau_D}
\]

(5)

The dislocation contrast:

\[
C = \frac{I_D}{I_B}
\]

(6)

can be expressed in terms of lifetimes. By substituting (2) and (4) into (6) we have:

\[
C = \frac{\tau' \tau_{nr}}{\tau_{nr} \tau' + \tau_{nr} \tau_D + \tau \tau_{nr}}
\]

(7)

\( C \) can also be expressed as a function of the measured lifetimes in the bulk (\( \tau \)) and at the dislocation (\( \tau' \)):

\[
C = 1 - \frac{\tau'}{\tau} \quad \text{(8) with } \tau' < \tau \text{ (black contrast)}
\]

Formulae (7) and (8) must be considered as very approximate since many factors have been neglected. Particularly, it has been assumed that the recombination centres are not saturated (thereby assuming linear relationship between injection and CL genera-
and also that the lifetimes do not depend on the injection density. Furthermore, the surface recombination has not been taken into account. The minority carrier lifetime approach for dislocation contrast has been reviewed by Holt and Datta [38].

Black dot contrast has been extensively studied by Davidson et al. [12, 27, 39, 40, 41] in n type GaP (nitrogen doping ranging from 2.10^{18} up to 5.10^{19} cm^{-3}). They found that the grown-in dislocations did not exhibit the same contrast but ranged from 10 to 40%. The same figure was obtained in GaP vapour phase S doped epitaxial layers. It was noticed that the contrast increased with sulphur doping and was a minimum for dislocations introduced by plastic deformation.

Lifetime measurements have been carried out at single dislocations and in bulk. In all cases, minority carrier lifetime is the smallest at the dislocation and increases with distance from the dislocation reaching the bulk value at approximately one diffusion length. Boulof and Schiller [9] obtained similar results for GaP. They gave the values $\tau = 150$ ns and $\tau' = 76$ ns for a contrast of 45% which is in agreement with formula (8). However, Steckenborn et al. [42] in GaAs (n type - 10^{16} cm^{-3}) found a lifetime increase at the dislocations (+ 29%) although the contrast was black (C = 76%). This contradictory result has not been satisfactorily explained.

The contrast is usually insensitive to the wavelength at which it has been measured: the shape of the spectrum is unchanged when approaching the dislocation apart from a slight variation which was reported by Davidson and Dimitriadis [41] at 720 nm in GaP. In InP too, no emission line specific to the presence of dislocations was found by Böhm and Fisher [43] by spatially resolved photoluminescence.

Rasul and Davidson [39] noticed that in the case of low nitrogen doped GaP samples, the dislocation contrast remained the same as the temperature was varied. In this specimen, $\tau_p$ was much greater than $\tau_{nr}$ and $\tau_d$ and therefore the contrast could be expressed as:

$$C = \frac{\tau_{nr}}{\tau_{nr} + \tau_d}$$

The dislocation contrast only depends on the relative non-radiative lifetimes at the dislocation and in the bulk. If C is constant, it means that the temperature dependence of $\tau_{nr}$ and $\tau_n$ are the same. Although a specific non radiative mechanism at dislocations cannot be ruled out, this strongly suggests that the non radiative mechanism at the dislocation and in the bulk is the same. This experiment supports a non radiative mechanism at point defects which is enhanced in the vicinity of the dislocation.

Titmarsh and Booker [44] carried out a study of the dislocation contrasts as a function of their Burgers vector. By TEM, seventeen dislocations were characterized. They included screw, edge, 30, 45 and 60° dislocations. Each dislocation gave a similar black dot contrast of the same size and intensity in CL image. No correlation was found between the CL image and the dislocation nature.

In silicon, no single dislocation contrasts have been reported. Only grain boundaries have been visualized [45]. They exhibit a dark contrast.

b) Dot and halo contrast

This sort of contrast usually appears in highly doped semiconductors: at the lifetime contrast an effect due to variation of dopant concentration around the dislocation will be superimposed upon it. In their experiment on GaAs:Te (n = 4.5 \times 10^{18} cm^{-3}), Balk and al [46] correlated a shift in peak emission with Se concentration and therefore were able to show that the Se concentration decreased when approaching the dislocation. Presumably, Se precipitation occurring at the dislocation was responsible for this denuded region. CL increase (halo contrast) was therefore correlated to the dopant distribution around the dislocation. Similar observations were made by Boulof and Schiller [9].

Chu and al [47] made a detailed study in GaAs:Te with doping concentrations ranging from 10^{17} up to 5.10^{18} cm^{-3}. Black dot, dot and halo and halo contrasts were investigated. HV-TEM observations were carried out in order to establish a
correlation between the contrast observed and the nature of the crystal defect present. The interesting point is that, in many cases, the contrasts were not associated with a single dislocation but with many dislocations and/or precipitation dislocation loops. This study clearly shows that care must be taken before interpretation of CL contrasts. Parallel or simultaneous TEM observations are highly desirable.

3 "Unusual contrasts"

The first "unusual contrast" will be illustrated by the work of Petroff and al. [48] [49] carried out in a STEM allowing direct comparison between TEM and CL images. On a (001) Ga As substrate a hetero-epitaxial structure Ga AsP/Ga As/Ga Al As was grown by liquid phase epitaxy (LPE). After removing the Ga As substrate mismatches dislocations contained in the three layer specimen (1.5 µm in thickness) were observed. They consisted of a cross-hatched network of mainly 60° dislocations (orientations (110) and (110) and a few Lomer dislocations (b = 1/2 [110]). The 60° dislocations exhibited a "usual" dark contrast typical of enhanced non radiative recombinations. The two sets have not the same dislocation density. It has been demonstrated that the set which contains the greatest amount of dislocations (set 1) was generated before the set 2. The dislocations of set 2 are therefore more mobile and contain more kinks than those of set 1. However, it was found that the dislocation contrast for set 2 was lower than for set 1. Therefore, it can be said that kinks do not seem to play an important role in the assessment of the non radiative efficiency associated with a dislocation.

The "unusual contrast" refers to Lomer dislocations which do not exhibit any CL contrast. 60° dislocations are known to be dissociated whereas Lomer dislocations are presumably undissociated and have no dangling bonds. Therefore, it is thought that the peculiar core structure of Lomer dislocations should play a role in their neutral behaviour toward CL.

The second type of "unusual contrast" refers to a dislocation with CL enhancement at a particular wavelength. From EL, some evidence of dislocation emission at 0.5 eV in plastically deformed germanium was given by Ivanov [50] and Barth and al [51]. By PL carried out at 4K, Drozdov and al [52] showed that recombination radiation lines were associated with the presence of dislocations in silicon. Two strong lines (0.812 and 0.875 eV) and two weak lines (0.934 and 1.00 eV) were revealed.

Petroff [53] carried out CL observations on a molecular beam epitaxy (MBE) double heterostructure (Ga Al As/Ga As/Ga Al As) specimen. At E = 1.512 eV (D'X line), the dislocations exhibit a "usual" dark contrast. However, at E = 1.504 eV which correspond to an as yet unidentified bound exciton characteristic of MBE material, only the dislocations which had originated in the Ga As substrate changed to give a white contrast. Therefore, it was so thought that the unknown centre (impurity or point defect) clusters around the dislocations thus giving rise to the white contrast observed.

CL studies of dislocations in natural diamond were carried out by Lang et al. [54][55] by use of the CL topographic technique: the specimen is flooded with a stationary electron beam and the image recorded on film by a simple optical system. This experimental set-up allows analysis of the polarization of the light emitted by the specimen. The dislocations were found to generate a blue emission. In addition the dislocations, especially those contained in slip lines, emitted a polarized line with the E vector parallel to the slip plane. Pennycook et al. [56] obtained high resolution CL dislocation images in a STEM. No correlation was found between the CL efficiency and the dislocation Burgers vector. Moreover some dislocations did not emit any light and were out of contrast in CL imaging. However, it was reported by Sumida and Lang [57] that high energy electrons quench the light emission and could explain the bad correlation observed by Pennycook et al.

V - APPLICATIONS

1 Plastic deformation
Davidson et al [58] carried out plastic deformation on a GaP specimen at 700°C using a four-point bending apparatus. A cross-hatched pattern was revealed on a (110) face by CL examination. The angle between the two sets of lines was 70° and this was interpreted as the trace of the (111) slip planes. Individual dislocations with black dot contrast could be seen at the ends of the sample where the deformation was moderate.

Esquivel et al [59][60] introduced either α or β dislocations in n-Ga As bent crystals. No significant changes related to the type of dislocation were noticed by dislocation contrast, peak position or half peak width of the CL emission line.

Continuous CL examination of dislocation motion have been carried out by Maeda et al [61] by use of a deformation apparatus installed in the SEM chamber. CdTe and CdS were deformed at room temperature and 380°K respectively. The points of emergence of the dislocations exhibited a dark spot contrast. Dislocation sources and growth behaviour of slip bands can be observed.

In a recent paper, Maeda et al [62] were able to observe the glide motion of α and β dislocations in GaAs at different temperatures, and to study the effect of the electron-beam irradiation on the dislocation velocity. Above a critical temperature T_c (550 and 650°K for α and β dislocations respectively), the temperature dependence of the velocity followed an Arrhenius formula with an activation energy of 1 eV for α dislocations and 1.7 eV for β dislocations, and corresponded to velocity measurements realised in darkness. Below T_c, the activation energy changed to 0.3 eV and 1.1 eV for α and β dislocations. At 500°K, the mobility of α dislocations was found to increase by a factor of 10 compared to the mobility measured without irradiation. These results were interpreted in terms of the recombination enhanced defect motion (RDEM) mechanism. The reduction in activation energy (0.7 eV and 1.1 eV for α and β dislocations respectively), was related to the energy released by nonradiative recombination of excess carriers at dislocations.

2 Interface defects

In addition to the experiments of Petroff [48][49][53] already described, many authors have used the CL technique as a means of characterizing the density of misfit dislocations. Kasano and Hasoki [63] investigated GaAs_1-x P_x/GaAs graded layers by CL where x was varied from 0 to 0.4. From the shift of the band to band peak wavelength, they deduced the compositional profile (and thus the compositional gradient) and from the intensity variations they deduced a non radiative centre concentration (α dislocation density). These two quantities can be compared as a function of the shape of the gradient for different specimens. Schiller [64] has carried out the same kind of assessment of Ga_1-x In_x As/GaAs graded layers.

Umanskii et al [65] determined the critical value for δ/δ (a : lattice parameter) in the Ga_1-xIn_x As/Ga0.5 Al0.5 As system for which the deformation changes from elastic to inelastic. They found a value of 0.08 %. "Rake line defects" in the active layer of GaAs double heterostructure lasers have been visualised by Gaw and Reynolds in the transmission configuration [66].

3 LED and laser degradation

TCL studies of the degradation of light-emitting devices were undertaken by Chin et al who have presented a review on the subject [67]. The degradation of homojunction, graded band-gap GaAlAs : Si was studied in the transmission configuration [68]. Dark line defects (DLDs) are observed to originate at the substrate back surface and to extend towards the junction. Only at this stage were the DLDs observed in the electroluminescence image.

In agreement with previous work, it was confirmed by CL that, in GaAlAs double heterostructure LEDs, DLDs originate at pre-existing dislocations [69]. Similar observations were made by Lebailly et al [70] on GaAlAs heterojunction electroluminescent diodes. Therefore, CL can be used as a nondestructive technique to select materials that will produce devices with long lifetimes.
4 Semi-insulating Ga As

The cell structure of SI-Ga As ingots was revealed by Chin et al [71]. The dislocation observed in the dark spot contrast, delineated large regions (> 100 \( \mu \text{m} \)) free from dislocations. The luminescence efficiency immediately around the dislocations (0 \text{ – 5} \( \mu \text{m} \)) was found to be low, to increase over a 50 \( \mu \text{m} \) wide region and then to decrease again in the dislocation free region. Kamejima et al [72] were able to correlate the CL contrast of the cell structure with impurity segregation (Si, O, Cr) at the dislocations by use of the SIMS technique.

VI - CONCLUSION

The CL technique has undergone a rapid development in these last few years. Sophisticated experimental set-up have been realized, allowing contrast evaluation on monochromatic images, accurate lifetime measurements and examination at low temperatures. Further improvements are required in the long wavelength area (> 1.2 \( \mu \text{m} \)) to enable studies of narrow-gap semiconductors and transitions involving mid-gap levels.

In most cases the presence of impurities and/or point defects associated with dislocations can be suspected to explain the contrast behaviour of dislocations. There is still a need for fundamental experiments on "clean" dislocations correlated with a careful characterization including Burgers vector determination and study of TEM core structure (weak-beam, high resolution).

Finally, CL has proved to be a valuable non-destructive method in investigating the dislocation distribution and impurity inhomogeneities in semiconductors. However, the theoretical lifetime approach for dislocation contrast is not satisfactory in many instances as too many points are neglected, and a comprehensive CL theory is still required.

REFERENCES