3 Experiments

In this chapter, two main experimental methods, Raman scattering and cathodoluminescence are introduced to show how dislocations and their interactions with point defects are studied and how the related electrical and optical properties of a semiconductor are deduced. An introduction to the other methods such as secondary ion mass microscopy (SIMS), transmission electron microscope (TEM), and positron annihilation technique (PAT) is omitted despite their importance in the present investigations.

3.1 Raman Scattering

3.1.1 Fundamental principle of Raman scattering

Raman spectroscopy is based on the analysis of inelastically scattered light. Scattering occurs from optical phonons or other quasi-particles like optical magnons, plasma; even electronic excitations provide similar sources for the Raman process [49]. Macroscopically, if the frequency of the scattered photon, \( \omega_s \), is smaller than that of the incident photon, \( \omega_i \), the event is referred to as a Stokes process and a phonon is generated during the process. If \( \omega_s \) is greater than \( \omega_i \), an anti-Stokes process occurs, accompanied with the absorption of a phonon. Energy and Momentum conservation for a light-scattering process with phonon generation or absorption, as shown in Fig. 3.1, can be written as,

\[
\hbar \omega_i = \hbar \omega_s \pm \hbar \Omega, \\
\hbar k_i = \hbar k_s \pm \hbar q.
\]

where \( \Omega \) is the frequency of a phonon. \( k_i, k_s, \) and \( q \) are respectively the wave vector of the incident photon, the scattered photon and the phonon. '+' means the generation of a phonon, '-' means the absorption of a phonon. For 180° backscattering, the maximum allowed value of the wave vector of the phonon is: \( q_{\text{max}} = k_i + k_s \approx 2k_i \). Since \( k_i \) is the order of \( 10^6 \text{ cm}^{-1} \) in the visible and near infrared spectral range, much smaller by about two order of magnitude than the dimension of the first Brillouin zone, only the scattering at or near the center of the Brillouin zone can be accessed by the first-order Raman scattering.\(^*\)

Although the expression and diagram seem to suggest that only a phonon–photon interaction is responsible for a Raman scattering process, electrons are actually involved in the process, since the phonon–photon interaction is rather weak unless they both have comparable frequencies. When a visible photon excites Raman scattering in a semiconductor, it would firstly couple to electrons via the electron–photon interaction. Due to the interaction, the total energy of the electron system can be written as

\[ \hbar \omega_i = \hbar \omega_s \pm \hbar \Omega, \]

\[ \hbar k_i = \hbar k_s \pm \hbar q. \]

\(^*\)For instance, for a He–Ne laser with the wavelength \( \lambda = 632.8 \text{ nm} \), \( k_i = 2\pi/\lambda = 9.9 \times 10^5 \text{ cm}^{-1} \) is far below the first Brillouin zone boundary \( \pi/a \sim 10^9 \text{ cm}^{-1} \). Therefore, relative to the size of the first Brillouin zone, \( q \approx 0 \).

Figure 3.1: Momentum conservation for a light-scattering process with phonon generation.
3 Experiments

\[ H = H_0 + H_{er}, \]  
(3.3)

where \( H_0 \) is the unperturbed Hamiltonian, \( H_{er} \) is a perturbation term due to the electron–photon interaction [50],

\[ H_{er} = -e \mathbf{r} \cdot \mathbf{E}. \]  
(3.4)

Here \( \mathbf{E} \) is the electric field, \( e \) the electron charge, and \( \mathbf{r} \) the distance between the electron and the phonon.

Considering the electron–photon interaction, the Raman scattering process proceeds in three steps and can be described as follows [50],

1.) The incident photon excites the semiconductor into an intermediate state \( |a\rangle \) by creating an electron–hole pair.

2.) The electron–hole pair is scattered into another state \( |b\rangle \) by emitting a phonon via the electron–phonon interaction.

3.) The electron–hole pair in \( |b\rangle \) recombines radiatively by emission of the scattered photon.

### 3.1.2 Selection rule

In order to obtain the first-order Raman scattering, i.e. a Raman-active vibration, the Raman tensor

\[ \mathbb{R} = (\partial \chi / \partial \mathbf{Q})_0 \hat{\mathbf{Q}}(\mathbf{q}, \Omega) \neq 0, \]  
(3.5)

is introduced, which states that there must be a net change in the permanent dipole moment during the lattice vibration. In Eq. (3.5), \( \chi \) denotes the elastic susceptibility of the medium, \( \mathbf{Q} \) is the atomic vector displacement from an equilibrium position induced by the phonon, and \( \hat{\mathbf{Q}} \) the unit vector parallel to the phonon displacement. Raman scattering intensity \( I \) is given by

\[ I \propto \left| \mathbf{e}_i \cdot (\partial \chi / \partial \mathbf{Q})_0 \hat{\mathbf{Q}}(\mathbf{q}, \Omega) \cdot \mathbf{e}_s \right|^2. \]  
(3.6)

where \( \mathbf{e}_i \) and \( \mathbf{e}_s \) are the orientations of the polarizations of the incident and scattering lights, respectively. Therefore, if a vibration does not greatly change the polarizability, then \( \mathbb{R} \) will be nearly zero, and the Raman intensity will be very low. Eq. (3.6) indicates that a definite Raman tensor determines whether the scattered radiation vanishes for certain choices of the scattering geometries. In the case of GaAs, it belongs to the point group \( T_d \), whose irreducible representations \( A_1, E_1, \) and \( F_2 \) are Raman active. The Raman tensors in crystalline coordination (i.e. \( x - [100], \ y - [010], \) and \( z - [001] \)) are

\[
A_1 : \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & a \end{pmatrix}, \ E_1 : \begin{pmatrix} b + c\sqrt{3} & 0 & 0 \\ 0 & b - c\sqrt{3} & 0 \\ 0 & 0 & -2b \end{pmatrix}, \ E_2 : \begin{pmatrix} c - b\sqrt{3} & 0 & 0 \\ 0 & c + b\sqrt{3} & 0 \\ 0 & 0 & -2c \end{pmatrix}, \ F_{21} : \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & d \\ 0 & d & 0 \end{pmatrix}, \ F_{22} : \begin{pmatrix} 0 & 0 & d \\ 0 & d & 0 \\ 0 & 0 & 0 \end{pmatrix}, \ F_{23} : \begin{pmatrix} 0 & d & 0 \\ d & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},
\]

where \( a, b, c, \) and \( d \) represent the linearly independent components deduced from Eq. (3.5). While the Raman tensor components \( A_1, E_1, \) or \( E_2 \) can be found in the two-phonon or the second-order Raman spectra, no optical phonon belongs to \( A_1, E_1, \) or \( E_2 \) in the first-order Raman scattering of zinc-blende-type crystals such as GaAs [50]. Therefore, the Raman selection rules for the
backscattering geometry in the first-order Raman scattering of zinc-blende-type crystals are determined only by $F_2$ and shown in Table. 3.1(a), where the scattering configurations are represented as $k^*_i(e_i,e'_i)k^*_s$, where $k^*_i$ and $k^*_s$ are the direction of the incident and scattered photons, respectively. The first-order Raman spectrum of GaAs consists of a longitudinal optic (LO) phonon at 292 cm$^{-1}$ and a transverse optic (TO) phonon at 270 cm$^{-1}$. From the selection rule, only the LO mode is allowed in the backscattering geometry of the Raman microprobe for scattering from the (100) surface while it is prohibited for the (110) surface of GaAs. For disorder crystal or amorphous material, the selection rule is broken down.

Table 3.1: (a) Raman selection rules for backscattering geometries in zinc-blende-type crystal. Here, $x = [100], y = [010], z = [001], y' = [110], z' = [011], x'' = [111], y'' = [100], z'' = [111]$. The scattering configurations are represented as $k^*_i(e_i,e'_i)k^*_s$, where $k^*_i$ and $k^*_s$ are the direction of the incident and scattered photons; and $e_i$ and $e'_i$ are the orientations of the polarizations of the incident and scattering photons, respectively. (b) The first-order phonon modes in wurtzite GaN.

<table>
<thead>
<tr>
<th>Scattering geometry</th>
<th>Selection rule</th>
<th>TO phonon</th>
<th>LO phonon</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100) surface:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x(y',y)x(z,z)x$</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$x(y,z)x(z,y)x$</td>
<td>0</td>
<td>$</td>
<td>d_{LO}</td>
</tr>
<tr>
<td>$x(y',z')x(z,y')x$</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$x(y',y')x(z,z')x$</td>
<td>0</td>
<td>$</td>
<td>d_{LO}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Active in</th>
<th>Raman Shift (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_2$ low</td>
<td>Raman</td>
<td>144</td>
</tr>
<tr>
<td>$A_1$(TO)</td>
<td>Raman, IR</td>
<td>533</td>
</tr>
<tr>
<td>$E_1$(TO)</td>
<td>Raman, IR</td>
<td>561</td>
</tr>
<tr>
<td>$E_2$ high</td>
<td>Raman</td>
<td>569</td>
</tr>
<tr>
<td>$A_1$(LO)</td>
<td>Raman, IR</td>
<td>735</td>
</tr>
<tr>
<td>$E_1$(LO)</td>
<td>Raman, IR</td>
<td>743</td>
</tr>
<tr>
<td>$B_1$ low</td>
<td>silent</td>
<td></td>
</tr>
<tr>
<td>$B_1$ high</td>
<td>silent</td>
<td></td>
</tr>
</tbody>
</table>

Cubic GaN has a zinc-blende structure and belongs to the point group $T_d$, so the optical modes seen by the first-order Raman scattering are similar to GaAs, and comprise a doubly degenerate TO (552 cm$^{-1}$) and a single LO phonon (740 cm$^{-1}$). Wurtzite GaN belongs to the point group $C_{6v}$ having four atoms per unit cell. Group theory predicts eight sets of phonon modes in the first-order Raman scattering [see Tab. 3.1(b)] [51].

3.1.3 Electric effects

The Raman bands are sensitive to the bond length or inter-atomic spacing and can thus be associated with strain/stress in the crystal. A blue shift of the Raman frequency may be associated with a compressive stress, and a red shift with a tensile stress [52]. In semiconductors, the free-carrier concentration can change some Raman bands with respect of linewidth and intensity [53].
In highly doped polar semiconductors, the coupling between the LO phonons and plasma via the macroscopic electric fields splits the LO mode into two branches, \( L^- \) and \( L^+ \), which can inversely be applied to determine the free-carrier concentration from Raman scattering. In the presence of the free carriers, the total dielectric function of the semiconductor with the phonon frequency \( \omega \) is given by

\[
\epsilon(\omega) = \epsilon_\infty(1 + \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{LO}^2 - \omega^2}),
\]

(3.7)

By solving the equation \( \epsilon(\omega) = 0 \), two LO phonon–plasmon coupled modes, \( \omega_{L^+} \) and \( \omega_{L^-} \), can be obtained

\[
\omega_{L^+}^2 = \frac{1}{2} (\omega_{LO}^2 + \omega_p^2(q)) + \frac{1}{2} \left[ (\omega_{LO}^2 + \omega_p^2(q))^2 - 4\omega_p^2(q)\omega_{TO}^2 \right]^{1/2},
\]

(3.8)

\[
\omega_{L^-}^2 = \frac{1}{2} (\omega_{LO}^2 + \omega_p^2(q)) - \frac{1}{2} \left[ (\omega_{LO}^2 + \omega_p^2(q))^2 - 4\omega_p^2(q)\omega_{TO}^2 \right]^{1/2},
\]

(3.9)

\[
\omega_p^2(q) = ne^2/m^*\epsilon_\infty + \frac{3}{5} q^2 \vartheta_f^2.
\]

(3.10)

Here \( \omega_{LO} \) and \( \omega_{TO} \) are the LO and TO phonon frequencies, respectively. \( \omega_p(q) \) is the plasmon frequency, depending on \( n \) and the wave vector \( q \) of phonons.* \( \epsilon_\infty \) is the high-frequency dielectric constant, \( \epsilon_0 \) is the vacuum dielectric constant, \( m^* \) the electron or hole effective mass. \( \vartheta_f \) is the Fermi velocity [55],

\[
\vartheta_f = \frac{h}{m^*}(3\pi^2 n)^{1/3}.
\]

(3.11)

The second term in Eq. (3.10) arises from nonlocal effects due to the noncompressibility of the

---

* \( \omega_p \) from Eq. (3.10) is actually the angular vibrational frequency of plasma, \( \omega_p = 2\pi v_p \) and \( v_p \) the clock frequency of plasma. In most Raman spectra, a phonon frequency is generally represented by its wave number; correspondingly, the relationship between the wave number of plasma (1/\( \lambda_p \)) and \( \omega_p \) is: \( \omega_p = 2\pi c/\lambda_p \). \( c \) is the light velocity in vacuum.

---

Figure 3.2: Raman frequencies of the coupled plasmon–phonon modes in (a) n-type GaAs and (b) n-type GaN as a function of the free-electron concentration \( n \).
system \cite{55}. For a low wave vector $q$, this term is negligible. The plasmon–phonon coupled modes in GaAs and in GaN were calculated from Eqs. (3.8), (3.9) and (3.10) as a function of the free-carrier concentration and are shown in Fig. 3.2.

Since the LO mode observed arises from the surface top layer, which is carrier depleted while $L^-$ and $L^-$ is excited in the bulk region beneath the surface, it is possible to determine the carrier depletion depth or the carrier concentration near the surface by comparing the intensities of the LO and $L^-$ Raman modes. The intensities of LO and $L^-$ are governed by the following relationships \cite{55}

$$I(LO) = I_0(LO)(1 - e^{-2\alpha d}),$$

(3.12)

$$I(L^-) = I_0(L^-)e^{-2\alpha d},$$

(3.13)

where $I_0(LO)$ and $I_0(L^-)$ are the intensities of LO and $L^-$ in semi-insulating material and heavily doped material with negligible space charge region, respectively. For GaAs, $I_0(LO)/I_0(L^-)$ is equal to 2.65 \cite{55}. $\alpha$ is the adsorption coefficient for Raman probe light, depending on its wavelength. $d$ is the surface depletion depth given by

$$d = (2\varepsilon_0\varepsilon_F\Phi_B/e^2n)^{1/2},$$

(3.14)

where $\Phi_B$ is the built-in surface potential (for GaAs, 0.8 eV) and $\varepsilon_F$ the static dielectric constant. According to Eqs. (3.12) and (3.13), the ratio between LO and $L^-$ is

$$I(LO)/I(L^-) = (I_0(LO)/I_0(L^-))(e^{2\alpha d} - 1),$$

(3.15)

which allows the estimation of the depletion depth or thus the free-carrier concentration near the surface.

### 3.1.4 Constituents of Raman spectroscopy

An integrated Raman system, LABRAM from the Dilor company, was used in the present studies. The basic parameters of the LABRAM Raman microscope are listed in the following:

- Laser: He–Ne, 20 mW, polarized 500 : 1, wavelength 632.817 nm,
- Confocal hole: 0–1500 μm; CCD detector with the detection range from 400–1100 nm,
- $z$ resolution: ~ 1 μm; $xy$ resolution: < 0.5 μm,
- Spectral resolution: < 1 cm$^{-1}$.

![Figure 3.3: Schematic principle diagram of the proceeding of information in Raman spectroscopy.](image)

The principle diagram of the Raman microscope is schematically shown in Fig. 3.3. The confocal hole is actually limiting the region of the sample where the signal is collected from. By using the confocal hole, the analyzed surface is specially defined with the precision down to 0.1 μm at
best and adjustable; and the depth of focus is reduced to about 1 μm. As a result, the contrast in a collected image is increased and the back scattered light is minimized. In general, there are three sorts of resolutions for an optical microscope:

1.) $z$ resolution (depth discrimination)

$$\Delta Z = \frac{R_i \lambda}{4 \cdot NA^2}$$

2.) $xy$ resolution

$$\Delta R = \frac{0.61 \lambda}{NA}$$

3.) Spectral resolution

$$\Delta \omega [cm^{-1}] = \frac{10^7}{\lambda^2 [nm]} \Delta \lambda [nm] \quad \text{and} \quad \Delta \lambda = \frac{\lambda}{m_s N_g}.$$  

$R_i$ is the refraction index, $NA$ the numerical aperture of the objective, $N_g$ the number of the gratings, and $m_s$ is the order of the spectrum. In the case of our equipment, the spectral resolution is typically 1 cm$^{-1}$.

### 3.2 Cathodoluminescence (CL)

#### 3.2.1 Fundamental principle of CL

Cathodoluminescence is the emission of light under electron bombardment. In general, it results from the radiative recombination of non-equilibrium charge carriers like electron–hole pairs excited by the incident electron beam. In semiconductors, the luminescence can be achieved by several radiative transitions between the conduction band ($E_c$), the valence band ($E_v$), exciton ($E_e$), donor ($E_d$), and acceptor ($E_a$) levels, as shown in Fig. 3.4. Sometimes, the radiative transitions are accompanied by non-radiative processes due to, e.g., the Auger effect or emissions of phonons. The energy of an emitted photon equals the difference between the initial and final energy levels of an excess electrons minus the energy of possibly emitted phonons accompanying the process of the emission of the photons. In particular, for the donor–acceptor pair recombination, the energy of an emitted photon depends further on the pair separation [56],

![Figure 3.4: Schematic diagram of radiative recombination processes of electron–hole pairs between the conduction band ($E_a$), the valence band ($E_v$), exciton ($E_e$), donor ($E_d$), and acceptor ($E_a$) levels in a semiconductor.](image)
\[ h\nu = E_g - E_d - E_a - mE_{ph} + \frac{e^2}{4\pi\epsilon_0}\varepsilon r. \]  

(3.16)

where \( m \) is the number of the emitted phonons with an energy of \( E_{ph} \), and \( r \) the donor–acceptor pair separation.

In principle, the CL intensity with an energy \( \hbar\nu \) collected by an ideal spectrometer can be mathematically calculated by the integral of the radiative recombination over the volume \( V \) excited by the incident electron beam [57],

\[ I_{CL}(\hbar\nu) = Q(\hbar\nu) \int_0^\Theta \sin\Theta d\Theta \int_V d^3r \frac{\tau_e}{\tau_{rad}} \Delta n(r) \exp \left( \frac{\alpha(\hbar\nu)z}{\cos\Theta} \right), \]  

(3.17)

where \( Q(\hbar\nu) \) is the quantum efficiency of the detector, \( \Theta \) the 3D angle within which the emitted photons can enter the detector, \( \alpha(\hbar\nu) \) the optical absorption coefficient, and \( z \) the incident depth of the electron beam. \( \tau_e \) is the effective lifetime of excess minority carriers, \( \tau_{rad} \) their radiative lifetime, and \( \Delta n(r) \) the density of the electron–hole pairs (excess minority carriers) available to recombination. Eq. (3.17) states that the CL intensity is proportional to \( \Delta n(r) \) and to the ratio of \( \tau_e \) to \( \tau_{rad} \). Since dislocations are centers with high non-radiative recombination rate, \( \tau_e \) at a dislocation can be calculated by

\[ \frac{1}{\tau_e} = \begin{cases} \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nonrad}} & \text{(beyond the dislocation core, i.e. } r > r_0) \text{),} \\ \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nonrad}} + \frac{1}{\tau_{dislocation}} & \text{(within the dislocation core, i.e. } r < r_0) \text{).} \end{cases} \]  

(3.18)

\( \tau_{dislocation} \) is the non-radiative lifetime of excess minority carriers associated with dislocations, \( \tau_{nonrad} \) the non-radiative lifetime through the other recombination centers. \( \Delta n \) near a dislocation can be expressed as [58–60]

\[ \Delta n(r) = g_r \tau_e [1 - \exp(-r/L_e)], \]  

(3.19)

where \( g_r \) is the generation rate of the minority carriers, depending on the electron beam energy \( E_{beam} \) and current \( I_{beam} \), as well as the ionization energy \( E_i \) (i.e., the energy required for the formation of an electron–hole pair): \( g_r = E_{beam} I_{beam} (1 - \eta_f)/eE_i \). \( \eta_f \) represents the fractional electron-beam-energy loss due to backscattered electrons [56]. \( r \) is the distance from the dislocation, \( L_e = \sqrt{D\tau_e} \) the effective diffusion length of the minority carriers, and \( D \) their diffusion coefficient. If it is assumed that the probability for the recombination of an electron–hole pair through a certain recombination path \( p \) is \( \zeta_p \), an expression such as

\[ I_p \propto \begin{cases} \zeta_p C_p \frac{\Delta n(r)}{\tau_{rad}} & \text{(} r > r_0 \text{),} \\ 0 & \text{(} r < r_0 \text{).} \end{cases} \]  

(3.20)

can be given. Here \( C_p \) is the density of transition paths \( p \). Since dislocations are widely assumed to be non-radiative recombination centers, almost no luminescence appear at the dislocation core, i.e. \( I_p \approx 0 \). Particularly for shallow-level-donor doping in GaAs, Eq. (3.20) is valid only when the concentration of the shallow-level donors is below its solubility limit, above which the luminescence intensity decreases with increasing dopant concentration because of the formation of dopant-related precipitates acting as non-radiative centers [61, 62].

### 3.2.2 Effect of external conditions on CL spectra

Since CL spectra are connected to the band gap or to the energy levels in the band gap, any variation of these levels must have an important influence on a luminescence band in the CL spectra.
The intensity and peak position of a luminescence band depend on several external parameters, such as temperature, pressure and the free-carrier concentration. Therefore, by monitoring the energy positions of the luminescence bands in the CL spectra, the information on the influence of temperature, pressure and the free-carrier concentration on the band gap and the energy levels in the band gaps can be obtained. As well known, the band gap becomes narrower to result in a red shift of the band-to-band luminescence with increasing temperature.

Some studies have found that the band gap or the defect-related luminescence bands become wider and shift up to a higher-energy position with increasing pressure. As an example, Fig. 3.5 displays the band gap and the yellow luminescence (YL) band in GaN as a function of pressure.

As pointed out by Sernelius [65], there are three possible kinds of near band gaps contributing to the near-band-edge (NBE) transitions in doped semiconductors: the first band gap $E_{g,1}$ is the distance in energy from the bottom of the conduction band to the top of the valence band. The second band gap $E_{g,2}$ means the energy distance between a shallow-level donor state (or the bottom of the conduction band) and the top of the valence band (or a shallow-level acceptor state). Finally, $E_{g,3}$ denotes the energy difference between a shallow-level donor and a shallow-level acceptor states if the vertically optical transition between them is allowed. Given the unperturbed band gap is $E_g$, the band-gap shift is defined as

$$\Delta E_{g,i} = E_{g,i} - E_g, \quad i = 1, 2, 3$$

### Figure 3.6: Calculated band-gap shift of (a) GaAs and (b) GaN as a function of the free-carrier concentration. The data on GaAs are taken from Ref. [65] and on GaN from Ref. [66].
In heavily doped semiconductors, where donor or acceptor states enter the conduction or the valence band, $\Delta E_{g,3}$ equals the so-called Burstein–Moss shift when no interactions are present between electrons (holes) and ions, i.e. $\Delta E_{g,3}$ increases with the free-carrier concentration [65]. The various band gaps in GaAs are shown in Fig. 3.6(a) as a function of the free-carrier concentration. On average, the total band-gap shift $\Delta E_g = (\Delta E_{g,1} + \Delta E_{g,2} + \Delta E_{g,3})/3$ decreases firstly with the free-carrier concentration up to about $2.0 \times 10^{19}$ cm$^{-3}$, above which it increases with the free-carrier concentration, similar to the case in GaN [compare (a) and (b) in Fig. 3.6].

The present CL investigations were carried out on a JSM 6400 or a BS 300 scanning electron microscope (SEM). A photomultiplier, a germanium (Ge), or a charge coupled device (CCD) detector and a computer-controlled monochromator were used to process the corresponding CL images or spectra. It is sometimes necessary to correct the spectra obtained by cathodoluminescence microscopy according to the quantum efficiency of the detector used in order to determine accurately the energy position and the intensity of a luminescence band. The range of the detected wavelengths depends on the type of the detectors. The effective wavelength detected by a Ge detector ranges from 800 nm to 1800 nm. The CCD used at present is front illuminated CCDs with the effective range of the detected wavelengths from 400 to 1100 nm. The efficiencies of the Ge and the CCD detectors as a function of the wavelength are shown in Fig. 3.7.

Figure 3.7: Quantum efficiency of (a) the Ge detector and (b) the CCD used as a function of the wavelength.