Absorption coefficient of various semiconducting materials

In this teaching module, we explain a technique to extract the absorption coefficient of various semiconducting materials as a function of wavelength by digitizing published experimental data and fitting the data with an analytic expression. This allows us to determine the parameter α_0 with is the basis of a simple analytic expression for the absorption coefficient as a function of energy, $\alpha(E)$. Finally we determine α_0 for various direct-gap and indirect-gap semiconductor materials.

Absorption coefficient

The ***absorption coefficient***, α, is a property of a material which defines the amount of light absorbed by it. The inverse of the absorption coefficient, α^{-1}, is the average distance traveled by a photon before it gets absorbed.

The inverse of the absorption coefficient, α^{-1}, also is the distance at which its intensity of light is reduced to a value 1/e (~36%) of its original intensity. The light intensity as a function of distance z is given by

$$I(z) = I_0 \, e^{-\alpha z} \, . \tag{1}$$

We classify materials as ***opaque***, ***translucent*** and ***transparent*** according to the absorption strength of these materials. Glass, for example a window pane, is transparent, while a silicon wafer is opaque to visible-spectrum light. A transparent material has a smaller absorption coefficient than an opaque material.

Absorption in semiconductors

Electrons in the valence band of a semiconductor can absorb photons whose energy are higher than the bandgap energy, E_g, and jump to the conduction band. The absorption coefficient, $\alpha(E)$, for an energy E higher than the bandgap energy is given by

For a direct semiconductor:
$$\alpha(E) = \alpha_0 \sqrt{\frac{E - E_g}{E_g}} \tag{2}$$

For an indirect semiconductor:
$$\alpha(E) = \alpha_0 \left(\frac{E - E_g}{E_g} \right)^2 \tag{3}$$

The photon energy E, is given by $h\nu = hc/\lambda$ where λ is the wavelength of light. Thus the absorption coefficient of a material depends on the wavelength of light incident on it.

Comparatively lesser absorption takes place for energies below the bandgap due to Urbach absorption and free carrier absorption. The Urbach tail, shown in ***Figure*** 1, is caused by phonon-assisted absorption and other mechanisms that introduce a potential fluctuation which leads to local variations of the band edges [1].

For even lower energies, free-carrier absorption plays the dominant role. Free carrier absorption is proportional to the free-carrier concentration.

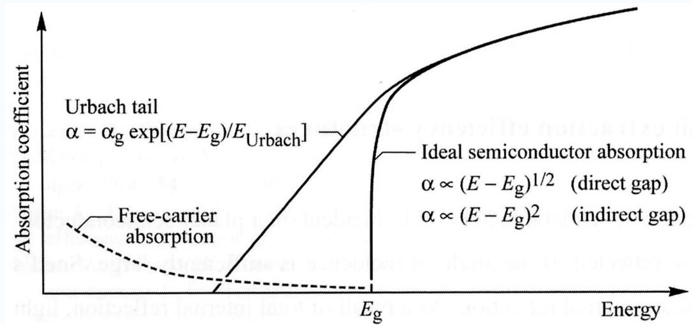

Figure 1: Absorption coefficient of a semiconductor with bandgap energy E_g versus energy (after Reference [1]).

Analyzing the absorption coefficient

Published graphs of the absorption coefficient as a function of photon energy for various semiconducting materials can be found at http://www.ioffe.rssi.ru/SVA/NSM/Semicond. ***Figure*** 2 shows the absorption coefficient of GaN at 293K as a function of the photon energy.

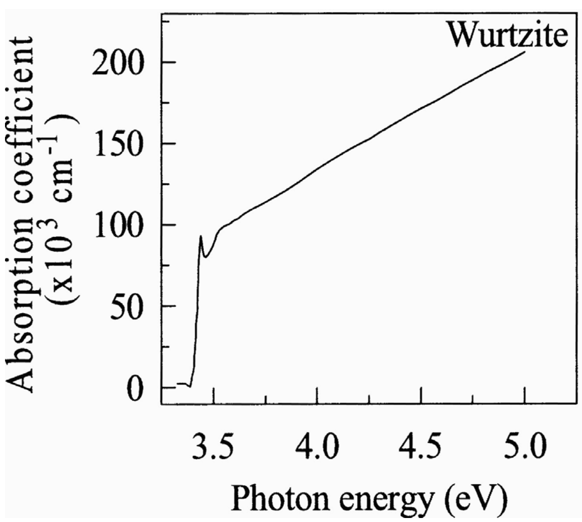

Figure 2: Experimental absorption coefficient of wurtzite GaN at 300 K (after Reference [2]).

Engauge (http://digitizer.sourceforge.net/) is a software program that converts an image file showing a graph or map, into numerical data. This program, first starts out by initializing the axes. The initialization is followed by "segment filling" the graph, which essentially adds points on to the graph. A snapshot of the Engauge Digitizer software in action is shown in ***Figure*** 3.

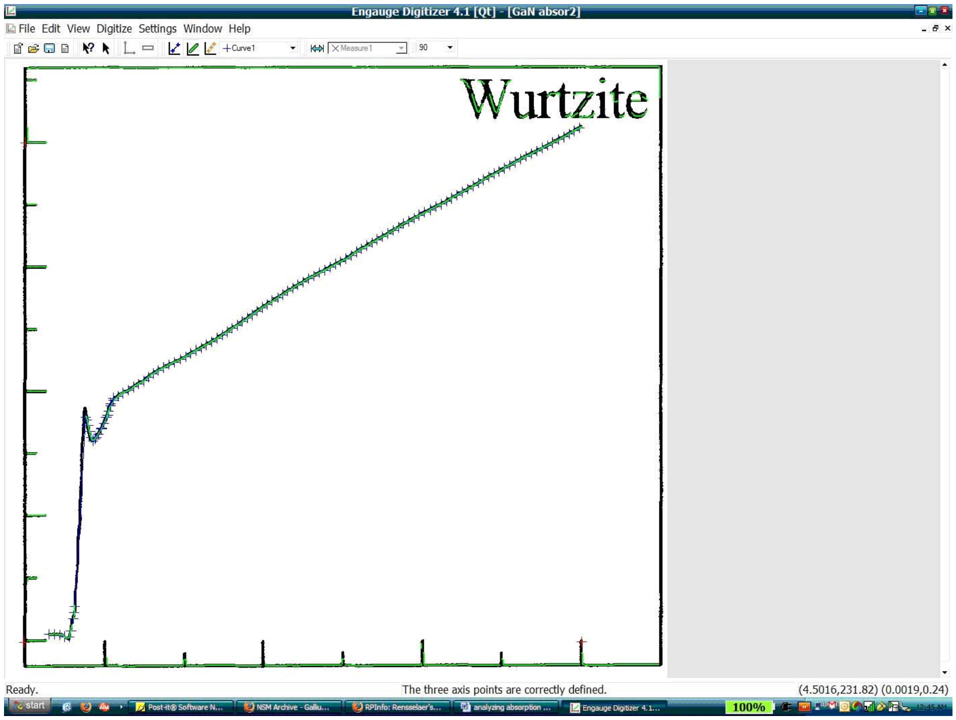

Figure 3: A snapshot of the software, Engauge Digitizer, in action.

The data can then be exported as "comma-separated-values file" (a .csv file). This file can be opened in programs such as Microsoft Excel. This exported Excel file contains the data values of the graph. Each axis occupies one column. The data points can then be graphed using Excel. A sample of the data is shown in ***Table*** 1.

Photon Energy (eV)	**Absorption coefficient of GaN at 293K** (cm^{-1})	$\alpha_0 = 2 \times 10^5\ cm^{-1}$	$\alpha_0 = 3 \times 10^5\ cm^{-1}$	$\alpha_0 = 4 \times 10^5\ cm^{-1}$
3.40	14.38	14.83	22.24	29.66
3.44	89.83	24.68	37.03	49.37
3.44	88.86	25.59	38.38	51.18
3.44	86.66	26.46	39.70	52.93
3.45	84.22	27.73	41.59	55.46
3.45	81.77	28.54	42.81	57.08
3.46	80.55	29.71	44.56	59.42
3.47	81.28	61.65	46.24	30.82

Table 1: Experimental absorption coefficient of GaN at 293 K versus photon energy and calculated absorption coefficient for different values of α_0.

The family of curves are calculated using $\alpha(E) = \alpha_0 \left[(E - E_g) / E_g \right]^{1/2}$ where E_g is 3.39 eV, and $\alpha(E)$ is the absorption coefficient of GaN at 293K. E is the photon energy and α_0 has a value of $2 \times 10^5\ cm^{-1}$, $3 \times 10^5\ cm^{-1}$ and $4 \times 10^5\ cm^{-1}$ for the different columns. ***Figure*** 4 shows the family of theoretical curves along with the experimental data.

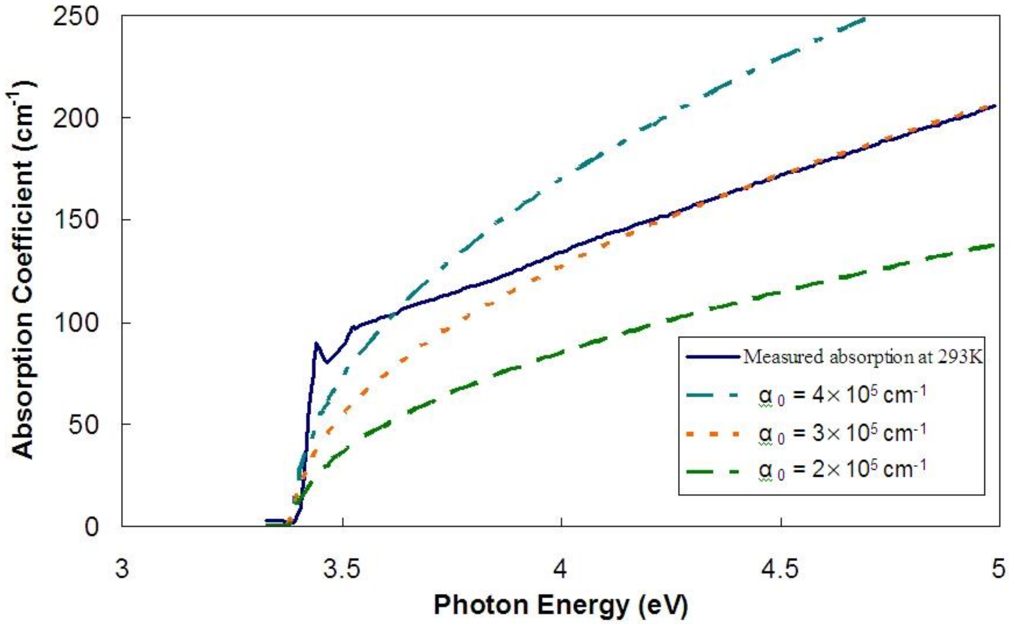

Figure 4: Experimental absorption coefficient of GaN versus photon energy. Also shown are three theoretical curves that are attempts to fit the experimental data.

Inspection of ***Figure*** 3 reveals that the best fit amongst the family of curves is for $\alpha_0 = 3 \times 10^5$ cm^{-1}. A similar analysis is done for various semiconductor materials. For direct-gap and indirect-gap materials we use Equation (2) and (3), respectively. The results of this analysis including the values for α_0 are given in ***Table*** 2.

Material	**Direct or Indirect Gap**	α_0
GaN	Direct	3×10^5 cm^{-1}
AlN	Direct	1.2×10^6 cm^{-1}
InN	Direct	$1 - 1.5 \times 10^5$ cm^{-1}
InP	Direct	5×10^4 cm^{-1}
GaAs	Direct	2.3×10^4 cm^{-1}
InAs	Direct	$1 - 1.6 \times 10^5$ cm^{-1}
Si	Indirect	1×10^4 cm^{-1}
Ge	Indirect	5×10^4 cm^{-1}

Table 2: Room temperature absorption coefficient values, α_0, for different semiconductors.

References

[1] Schubert, E. Fred, *Light-Emitting Diodes*, 2nd edition: Cambridge University Press, 2006.
[2] NSM Archive-Physical Properties of Semiconductors. Ioffe Institute; see < http://www.ioffe.ru/SVA/NSM/ Semicond/index.html >
[3] < http://digitizer.sourceforge.net/ >