Optical transmittance measurements and bandgap energy

Theory

This teaching module shows how to determine the bandgap energy of a semiconductor from an optical transmittance measurement through an epitaxial layer deposited on a transparent substrate. Consider a semiconductor with thickness d and an absorption coefficient that is given by

$$\alpha(E) \quad \propto \quad \sqrt{E - E_g} \ . \tag{1}$$

Light incident on the semiconductor wafer will be partially reflected due to Fresnel reflection with Fresnel power reflection coefficient being given by

$$R_1 \quad = \quad \left(\frac{n_s - 1}{n_s + 1} \right)^2 \ . \tag{2}$$

Assume that the intensity of the light incident on the semiconductor is I_0. Then the light intensity just inside the semiconductor, I_s, is given by

$$I_{s1} \quad = \quad I_0 \, (1 - R_1) \ . \tag{3}$$

Thus the light intensity at the lower end of the semiconductor layer is given by

$$I_{s2} \quad = \quad I_0 \, (1 - R_1) \ \exp(-\alpha \, d) \tag{4}$$

We further consider Fresnel reflection at the semiconductor-substrate and substrate-air interfaces and denote them by R_2 and R_3. Furthermore, if the substrate surface is not polished (i.e. has surface roughness), there will be optical scattering losses. Assuming that the fraction of light that does not reach the detector due to scattering at the unpolished substrate surface is S, then the measured optical transmittance through the wafer is given by

$$T(E) \quad = \quad \frac{I_{\text{transmitted}}}{I_0} \quad = \quad (1 - R_1)\,(1 - R_2)\,(1 - R_3)\,(1 - S) \ \exp(-\alpha \, d) \ . \tag{5}$$

where we have neglected interference effects and multiple reflections. Solving the equation for the absorption constant $\alpha(E)$ yields

$$\alpha(E) \quad = \quad -\frac{1}{d} \ln \left(\frac{T(E)}{(1 - R_1)\,(1 - R_2)\,(1 - R_3)\,(1 - S)} \right) . \tag{6}$$

Normalizing the transmittance data so that $T_{\text{normalized}} = 100\%$ in the transparent region ($h\nu < E_g$), allows us to neglect Fresnel reflections and scattering losses. We then can write

$$\alpha(E) \quad = \quad -\frac{1}{d} \ln \left(T_{\text{normalized}}(E) \right) . \tag{7}$$

According to Eq. (1), $\alpha(E)$ has a square-root dependence on E. Accordingly, $\alpha(E)^2$ has a linear dependence on E. Thus by plotting $\alpha(E)^2$ versus E and extrapolating the linear part of the measurement to zero, the value of the bandgap energy is obtained.

Experimental procedure

- Measure Spectral Transmittance $T(\lambda)$ using Jasco photospectrometer and convert data to $T(E)$
- Normalize $T(E)$ so that $T_{normalized}(E) \leq 100\%$ in transparent regime ($h\nu < E_g$)
- Calculate absorption coefficient $\alpha(E)$ using Eq. (7)
- Plot $\alpha(E)$ versus E and check if absorption coefficient looks reasonable
- Plot $\alpha(E)^2$ versus E
- Make linear fit to experimental data in vicinity of bandgap energy (i.e. for $E > E_g$)
- Intersection point of linear fit with the abscissa is bandgap energy

Example

In this example, we measure the transmittance of a $d = 0.82$ μm $Al_xGa_{1-x}N$ epilayer from sample RPI-2006-149 AlGaN. This sample consists of 2 AlGaN epilayers with different Al mole fractions grown on a single side polished sapphire substrate. The top layer has significantly lower Al mole fraction and thus the lower band gap energy. In the transmittance measurement, we expect to measure the data for the top layer only. Figure 1 shows the plot of the transmittance T versus wavelength λ.

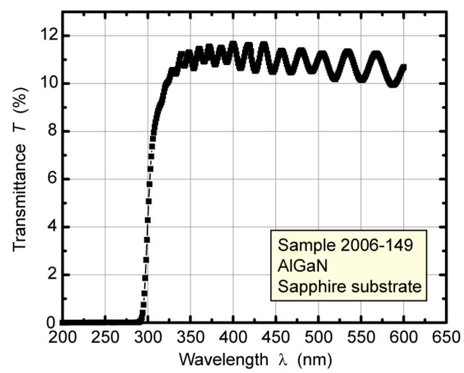

Fig. 1: Transmittance T versus wavelength λ.

The transmittance data is then normalized to its highest measured value (which is set to 100%) to obtain $T_{normalized}(E)$ and the wavelength is converted into energy E using the relation $E = 1239.5$ eV-nm/ λ. This data is plotted in Figure 2.

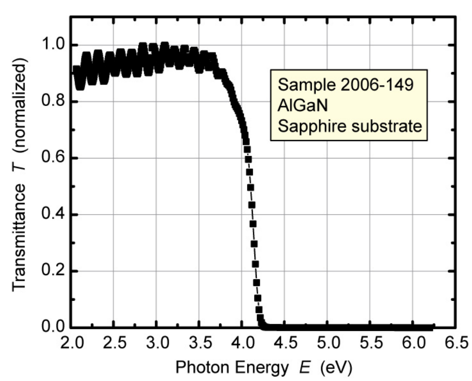

Fig. 2: Normalized transmittance $T_{normalized}$ versus energy E.

Finally, we calculate the absorption coefficient $\alpha(E)$ using Eq. (7). Figure 3 shows the plot of $\alpha(E)^2$ versus E.

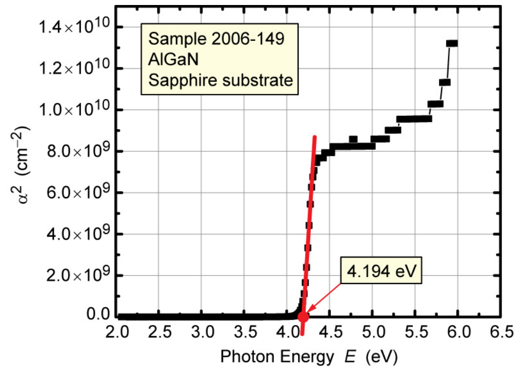

Fig. 3: Absorption Coefficient (squared) versus energy E.

We find E_g = 4.194 eV. Using the AlGaN bandgap energy versus composition plot shown in Figure 4, we determine the Al composition of the sample to be x = 35%.