IQE and all that jazz: the temperature dependence of semiconductor light emission

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For temperature dependences:

- Cool to ~10 K @ ~5 K per minute
- Take one whole spectrum (in 1 s) every 0.5 K or 1 K.
The conventional model, an activation energy $E_A$ separates a radiative (localised) state from a band of delocalised states, with a relative degeneracy ratio of $1:gT^{3/2}$.

The radiative fraction is then given by:

$$\text{IQE}(T) = \frac{I(T)}{I(0)} = \frac{1}{1 + gT^{3/2}\exp(-E_A/k_BT)}$$

which shows the well-known general form, with a nearly constant intensity up to a temperature $\sim E_A/10k_B$ followed by a fairly rapid decline as $T$ increases further.

Note: $E_A = k_BT_A; 1\text{ eV} \sim 11600\text{ K}$
Some comments on the R-NR model

- The $T^{3/2}$ dependence is relatively weak and is often ignored. It makes little practical difference to the goodness of fit for most data. Simplifying and approximating the formula* produces the Arrhenius form of the relation:

$$\frac{I(T)}{I(0)} = \frac{1}{1 + gT^{3/2}\exp(-E_A / k_BT)}$$

A plot of $\log(I)$ vs $1/T$ can be fitted asymptotically with a straight line to yield an estimate of $E_A$.

- IQE($T = 300$ K) is the value most often quoted, but the formula carries the implication that all semiconductor luminescence is 100% efficient at low temperatures: this is unlikely to be true.

- We can usefully define the half-power point at which temperature the luminescence intensity drops to half-maximum:

$$T_{1/2} = \frac{E_A}{k_B \ln G}$$

This parameter provides a ‘sanity check’ on the fitness of the model (see later).

*as is my wont
Introducing the sigmoidal fit

\[ \frac{I(T)}{I(0)} = \frac{1}{1 + \exp\left(\frac{T - E_A}{k_B T}\right)} \]

- Centroid 255 K
- Span 20 K
- Prefactor $2.6 \times 10^8$
- Activation energy 0.45 eV

All fits tend to deviate at low PL intensity, due partly to errors in background subtraction.

The sigmoid as a smoothed step function

$I(T) = \frac{1}{1 + \exp\left(\frac{T - C}{S}\right)}$

- $C$ - centroid ($= T_{1/2}$)
- $S$ - span
The temperature dependence of photoluminescence in a-Si: H alloys

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Abstract
Photoluminescence intensity observed near 1.3 eV in sputtered a-Si : H has been measured as a function of temperature for several samples prepared under differing conditions. The data are shown to obey an expression derived from a law of the form

$$\frac{\rho_{NR}}{\rho_R} \sim e^{T/T_0}$$

where $\rho_{NR}$ and $\rho_R$ are the probabilities for non-radiative and radiative recombination. We find $T_0 \approx 23$ K independent of sample preparation conditions.

The temp dependences are similar since the radiative fraction

$$\frac{\rho_R}{\rho_R + \rho_{NR}} \sim \frac{1}{1 + \exp\left(\frac{T}{T_0}\right)}$$

is a sigmoid with $T_{1/2} = 0$ K and $S = T_0$.
The fits are naturally weighted towards the low temperature region where intensities are higher.

High temperature intensity values suffer more from errors in background subtraction.

Comparing fits and fit parameters

The restricted range of intensities.

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Comparing fits and fit parameters

The restricted range of intensities.
Eu0 anomalous; Eu1 quasi-normal.

Eu0 absent; Eu1 normal.

Luminescence hysteresis
The anomalous (hysteretic) behaviour here can be described by the usual equations if we allow negative energy as a fit parameter.

The shaded region has a normal temp. dependence: whether warming or cooling, the intensity is lower at higher temperature.
A rising step is just the complement of a falling step—Sigmoid Frond

\[
1 - \frac{1}{1 + gT^{3/2} \exp\left(\frac{-E_A}{k_B T}\right)} = \frac{1}{1 + (1 / gT^{3/2}) \exp\left(\frac{E_A}{k_B T}\right)}
\]

\[
1 - \frac{1}{1 + \exp\left(\frac{T_{1/2} - T}{S}\right)} = \frac{1}{1 + \exp\left(-\left(\frac{T_{1/2} - T}{S}\right)\right)}
\]
fall \hspace{1cm} \text{rise}

Algebra never lies
Datafits are not perfect

\[ I_0 = 3.9 \times 10^5 \text{ cps} \]

\[ T_{1/2} = 25.6 \text{ K} \]

\[ S = 3.9 \text{ K} \]

\[ I_0 = 4.3 \times 10^5 \text{ cps} \]

\[ T_A = -180 \text{ K} \]

\[ g = 7.2 \times 10^{-6} \]
Odd behaviour of the BL band in high-resistivity GaN:Zn: **power-tuneable** thermal quenching

**Figure 2** Temperature dependence of the quantum efficiency of the BL band in high-resistivity Zn-doped GaN for selected $P_{\text{exc}}$.

**Figure 4** Dependence of the BL band intensity on the excitation power density at $T = 200$ K.

GaN:Zn (deep acceptor) with shallow donor and **Shockley-Hall-Reed** e-h recombination centre.

Temp-dependence and power-dependence

Fuji GN932
X350 nm ~1 mW cm\(^{-2}\)
11 K - 291 K
log(PL intensity)

Low power photoexcitation-
room temp. spectrum

High power cathodoexcitation-
room temp. spectrum
Fig. 2 $\text{Er}^{3+}$ emission intensity against host semiconductor temperature

- Materials are implanted with Er ions: $E = 330$ keV, $\phi = 10^{13}$ Er$^+$ cm$^{-2}$, $E_G$ values are given at room temperature.
  - a. Ga$_{0.33}$In$_{0.67}$As$_{0.44}$P$_{0.56}$ ($E_G = 0.807$ eV)
  - b. Si ($E_G = 1.12$ eV)
  - c. InP ($E_G = 1.27$ eV)
  - d. GaAs ($E_G = 1.43$ eV)
  - e. Al$_{0.17}$Ga$_{0.83}$As ($E_G = 1.67$ eV)
  - f. ZnTe ($E_G = 2.26$ eV)
  - g. CdS ($E_G = 2.42$ eV)
LUMINESCENCE OF ERBIUM IMPLANTED IN VARIOUS SEMICONDUCTORS: IV, III-V AND II-VI MATERIALS

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Summary and conclusions

• The temperature dependence of luminescence from semiconductors is well described by the conventional R-NR model, unless it isn’t.

• A parameter that can be extracted from the data is $E_A$, the activation/localisation/binding energy (delete as appropriate).

• More useful in a practical sense is the IQE (RT), but you may prefer to quote the half-power temperature $T_{1/2}$.

• In terms of the fitting parameters for the modified Arrhenius fit, $T_{1/2} = \frac{E_A}{k_B \ln G}$; for the sigmoidal fit $T_{1/2} = T_{1/2}$. (The derivation of an expression for $T_{1/2}$ in the conventional R-NR model is left as an exercise for Phil Dawson students.)

• In Reschikov’s work, a slight modification of the simple temperature-dependence model produces wonderful complications.

• A reanalysis of Favennec’s data 25 years on teaches us that extrapolation is dangerous.