Cathodoluminescence of Rare Earth Ions in Semiconductors and Insulators

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Terms in the Title

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For the curious:
Q: Are rare earth elements rare?
A: Not particularly – they are all significantly more abundant than gold.
Q: Are rare earth elements “earth”?
A: No, “earth” is an archaic word for oxide.
Applications

Electrically pumped lasers, light sources, and light amplifiers
- REIs are already used in optically pumped lasers
- REIs have consistent emissions in the visible spectrum independent of host material
- create a display from different REIs in same host

Wide Bandgap Semiconductors
- Transparent to visible light
- Efficient REI emission – Ions can be electrically excited
- Can use semiconductor tricks – can make PN junctions to inject electrons
Experimental Setup

Monochromator

MIRRORS

Grating

PMT

SEM

e- beam (20kV)

Mirror

hv

AuPd coating
Sample (Eu doped AlN)

beam interaction volume
Interaction with the beam

- e-beam (20kV)
- Backscattered and secondary e-
- hv
- AuPd coating
- Sample (Eu doped AlN)

beam interaction volume
**Interaction with the beam**

- Collisions create electron hole pairs
- Electron Energy = 20KeV
- 620nm Photon Energy ≈ 2eV
What do we see?

Intensity vs. Wavelength

Intensity (arb units) vs. Wavelength (nm)
Questions

1. Is the process efficient? What is the limiting factor?
2. How do the REIs become excited?
   - Directly by beam electrons hitting the REIs?
   - Electron hole pairs transferred from the base material?
   - Is there an intermediate trap?
2 Energy Level System

- $N$ total ions, $N_e$ excited, and $N_g$ in the ground state
- $p$ pump rate, $k$ decay rate, $\tau = \frac{1}{k}$ decay time constant

\[
\frac{d}{dt} N_e = p N_e - k N_g = p N_e + k N_e - k N
\]

\[
\frac{d}{dt} N_e = -k N_e
\]
The Model

2 Energy Level System

- \( N \) total ions, \( N_e \) excited, and \( N_g \) in the ground state
- \( p \) pump rate, \( k \) decay rate, \( \tau = \frac{1}{k} \) decay time constant

\[
\frac{d}{dt} N_e = pN_e - kN_g = pN_e + kN_e - kN \\
\frac{d}{dt} N_e = -kN_e
\]

Solutions:

\[
N_e = \frac{pN}{p+k} \left( 1 - e^{-(p+k)t} \right) \\
N_e = \frac{pN}{p+k} e^{-kt}
\]
In spot mode, the beam just dwells on one spot. If we wait a moment:

\[ N_e \approx \lim_{t \to \infty} \frac{pN}{p+k} \left( 1 - e^{-(p+k)t} \right) = \frac{pN}{p+k} \]
The Model and Spot Mode

In spot mode, the beam just dwells on one spot. If we wait a moment:

\[ N_e \approx \lim_{t \to \infty} \frac{pN}{p+k} \left( 1 - e^{-(p+k)t} \right) = \frac{pN}{p+k} \]

However, this only really tells us about the ratio \( \frac{k}{p} \).

\[ N_e \approx \frac{pN}{p+k} = \frac{N}{1+\frac{k}{p}} \]
Output saturates – efficiency is not the limiting factor

Intensity is less than for photoluminescence (PL) – fewer REIs are being excited

That rules out direct excitation and direct host transfer
The beam only shines on a spot part of the time.

Finding the steady state is done numerically.

The frequency of the scan is varied.

The time average is fit to the data, determining $k$. 
Does The Model Work?

$k = 1.46 \times 10^6 \quad p = 1.60 \times 10^7$

$\tau = 6.82 \times 10^{-5}$ seconds is similar to the relaxation time of Eu

This does not show evidence for a trap
Shows a drop compared to Er in semiconductors.

Indicates that direct excitation is not the mechanism at work.

We’re still investigating this material.
Conclusion and Summary

- Difference in intensity between CL and PL, and dependence on host material, suggests direct excitation is not at work.
- However, the measured time constant is similar to that of Eu, meaning that if there is a trap, it is faster.
- Still, something besides the number of REIs and the efficiency must be the limiting factor – traps are likely to be it.
- More measurements are needed – taking data is slow with the current setup.