Temperature sensor for Scanning Thermal Microscopy based on photoluminescence of microcrystal

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The final purpose:

To develop a device calibrated in temperature and capable of acquiring images of local temperature at sub-micrometric scale.

Development of a temperature sensor for measuring local temperatures based:

- on a thermal-resistive probe of SThM (Scanning Thermal Microscope)
- on photoluminescence of crystal \( \text{Cd}_{0.7}\text{Sr}_{0.3}\text{F}_2: \text{Er}^{3+}(4\%)-\text{Yb}^{3+}(6\%) \)

(This luminescent material has the particularity to give an emission spectrum with intensities sensitive to small temperature variations)

A microcrystal of about 10µm in diameter is glued at the probe extremity.

Interest: Temperature can be obtained in two distinct ways:

- one from the thermal probe parameters and
- the other from the green photoluminescence generated by the Er ions.

Presentation of first results
**Principle of AFM (Atomic Force Microscope)**

- **Force feedback loop**
- **Sample**
  - Image of sample topography (100µm*100µm max))
  - Image of sample thermal conductivity
  - Image of sample temperature

**SThM = AFM + Thermal probe**

**Purpose**

- Image of sample thermal conductivity
The thermal probe

Pt/Rh wire = Heat sensitive element of the probe

\[ R_{\text{pt-rh10}} = R_0(1 + \alpha(T_{\text{op}} - T_0)) \quad \text{with} \quad \alpha = 0.00165 \text{ K}^{-1} \]
Red to green excitation process

Energy (cm⁻¹)

0 5000 10000 15000 20000 25000

Er³⁺

$^4F_{9/2}$

$^2H_{11/2}$

$^4S_{3/2}$

$^4F_{7/2}$

$^4I_{11/2}$

$^4I_{13/2}$

$^4I_{15/2}$

$^4F_{9/2}$

$^4I_{11/2}$

$^4I_{13/2}$

$^4I_{15/2}$

652 nm

540 nm 549 nm 522 nm

19130

18500

18380

Thermally coupled emitting levels (3)

Metastable level

Red absorption

Non-radiative desexcitations

Energy transfer between Er ions

Green emissions
Experimental set-up

Temperature measurement by photoluminescence of doped microcrystal

The diagram shows the experimental set-up for temperature measurement using photoluminescence of a doped microcrystal. The set-up includes a tunable laser emitting at 652 nm, a thermal probe heated by Joule effect, and various components such as photomultiplier, monochromator, lock-in amplifier, and recorder. The electrical circuit for the thermal probe is also depicted.
Check of the emission spectrum of microcrystal comparatively to the crystal one

Temperature measurement by photoluminescence of doped crystal

A rectangular crystal plate 0.3 mm thick of this luminescent material is placed in a heater whose temperature is measured by a thermocouple.
Green fluorescence spectrum emitted by the erbium ions excited by the dye laser operating at 652 nm

The temperature behavior of microcrystal is similar to the crystal one.
Validation of Boltzmann’s law

\[
\frac{I_{522}}{I_{549}} = C \exp\left(-\frac{\Delta E}{kT}\right) \quad \Delta E : \text{Energy gap between the emitting levels}
\]

\[
\frac{I_{522}}{I_{540}} = C' \exp\left(-\frac{\Delta E'}{kT'}\right) \quad k = 0.6951 \text{ K}^{-1} \text{.cm}^{-1} : \text{the Boltzmann constant}
\]

Experimental data of \(\ln(I_{540}/I_{522})\) and \(\ln(I_{549}/I_{522})\)

slopes → \(\Delta E/k\)

slope of 908 → \(\Delta E = 631 \text{ cm}^{-1} (630 \text{ cm}^{-1})\)
slope of 1089.5 → \(\Delta E' = 757 \text{ cm}^{-1} (750 \text{ cm}^{-1})\)
Application of Boltzmann’s law for determination of the temperature of doped microcrystal

\[ T = \frac{\Delta E}{k} \left( \ln C + \ln \left( \frac{I_{549}}{I_{522}} \right) \right) \]

\[ \Delta T = T - T_0 \]

\[ T' = \frac{\Delta E'}{k} \left( \ln C' + \ln \left( \frac{I_{540}}{I_{522}} \right) \right) \]

\[ \Delta T' = T' - T_0 \]

No heating of microcrystal by excitation laser

Set of laser power at 4.5 mW
Temperature rise of doped microcrystal when the probe is heated

at laser power 4.5mW

from \((I_{540}/I_{522})\) and \((I_{549}/I_{522})\)

\[ \frac{I_{540}}{I_{522}} \rightarrow \Delta T' \]

\[ \frac{I_{549}}{I_{522}} \rightarrow \Delta T \]

Electrical current intensity in the probe
Estimation of the thermal probe temperature

Probe heated by Joule effect (continuous current)

Probe temperature: \( T_{Pt/Rh} \)

\[
T_{Pt/Rh} - T_0 = \frac{R - R_0}{\alpha R_0}
\]

- \( R \): electrical resistance of Pt/Rh filament at temperature \( T_{Pt/Rh} \)
- \( R_0 \): reference electrical resistance at reference temperature \( T_0 \)
- \( \alpha \): coefficient of sensitivity in temperature of Pt/Rh wire \( \alpha = 0.00165 \text{ K}^{-1} \)
- \( T_0 \): ambient air temperature

⚠️ \( T_{Pt/Rh} \) = Temperature of the Pt/Rh filament averaged over its length (200 µm)

≠ Temperature at the probe apex (\( T_{apex} \))
**Temperature at the probe apex**

Microcrystal is at the probe extremity => Determination of temperature at the filament apex.

Thermal modeling => Temperature distribution in the Pt/Rh filament from its average temperature experimentally estimated.

**Modeling of the half probe**

$h, h_w, h_{ext}$ : thermal exchange coefficients

$h$ : thermal exchange towards the surrounding air (1800 W.m$^{-2}$.K$^{-1}$). Estimation with minimization from experiments air /vacuum.


Temperature profile along the probe (half-probe)

In case of the probe in air, the temperature is maximal at the probe apex

\[ I = 36 \text{ mA} \]
\[ T_{\text{Pt/Rh}} = 64^\circ \text{C} \]
Comparison

- microcrystal temperature rises measured by photoluminescence
- the probe average temperature experimentally estimated
- temperature at the probe extremity obtained by modeling

Temperature rise of microcrystal measured by photoluminescence: \((\Delta T + \Delta T')/2\)

Average temperature along the probe (experimental result)
Size of the microcrystal (25 µm) => we can assume the microcrystal temperature is lower than the temperature of the probe extremity

In a first approach, if we consider the temperature at a distance of 10 µm in air from the filament surface assuming

Air = a conductive medium

Dependence on temperature of the Pt/Rh thermal conductivity
Correlation between temperature by photoluminescence and the thermal probe temperature taking the crystal size into account.
CONCLUSION

Temperature sensor based on photoluminescence of microcrystal codoped by Erbium and Ytterbium.

Microcrystal temperature of micrometric size from measurements of photoluminescence intensities and applying the Boltzmann’s law.

By comparing the results with those obtained by modeling and from the characteristics of the thermal probe:

- the microcrystal temperature is not the temperature of the probe apex but is lower and corresponds to the local temperature located in air near the probe apex.

It is possible to calibrate a temperature sensor from the photoluminescence.

We continue to work in this direction for the development of temperature imagering and using a nanocrystal rather than a microcrystal.
Thank you for your attention