TeO_2 scintillating crystals growth and properties

I. Dafinei[a], M. Diemoz[a], M. Fasoli[b], I. Földvári[c], E. Longo[a], F. Moretti[b], Á. Péter[c], F. Somma[d], A. Vedda[b]

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[c]Research Institute for Solid State Physics and Optics, Budapest, HUNGARY
[d]Università degli Studi Roma Tre – Dipartimento di Fisica, Rome, ITALY

Abstract

The advantages of using hybrid detectors (scintillating bolometers) in rare event searches like Double-Beta Decay or Dark Matter interaction are discussed.

The possibility to produce scintillating TeO_2 crystals is emphasized and the results of optical transmission and X ray excited steady-state luminescence measurements performed on pure and doped TeO_2 crystals are presented.

1

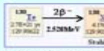
CUORE experiment

•observation and measurement of the neutrinoless double-beta decay

$(Z, A) \rightarrow (Z+2, A) + 2e^-$

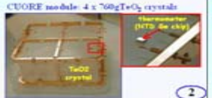
•unique way to look for neutrino masses of the Majorana type

At extremely low temperatures (~7-10 mK), even small energy release in a crystal results into a measurable temperature rise (heat capacity ~ T/T_D^3 where T_D is the Debye temperature)



Crystals of TeO_2 may act both as a detector and source

CUORE module: 4 x 760g TeO_2 crystals



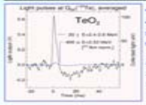
2

CUORE detector will consist of an array of 988 TeO_2 bolometers arranged in 19 towers of 52 crystals each.

goal: achieve a background rate in the range 0.001 to 0.01 counts/keV/kg/y at the $0\nu\beta\beta$-decay transition energy of ^{130}Te (2.528 MeV).

scintillation may help to discriminate the type of interacting quantum with an immediate effect on background reduction

What is known on scintillation in TeO_2



- LY=0.67% BGO
- no indication on spectrum or decay characteristics

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10th LTD, Genoa, 7-11 July 2003

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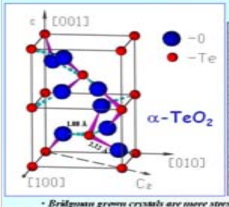

paratellurite

Characteristic	value
Chemical Formula	TeO_2
Molecular Weight	159.61
Crystal Class	Tetragonal
Density, g/cm^3 at 293 K	6
Melting Temperature (K)	1006
Hardness (Mohs)	4
Solubility in water	None
Color	Clear
Transmittance Range, µm	0.33-5.0
Refractive index (λ=500nm)	n_o=2.3194
	n_e=2.4829
Melting point (°C)	733
Thermal Expansion at 295K, 1/K	
normal to <001>	19.5 x 10^{-6}
parallel to <001>	6.10 x 10^{-6}
Thermal Conductivity, mW/cm K	30
Mechanical Impedance, kg/m² sec	3.6 x 10^6

- *Bridgman grown crystals are more stressed than Czochralski ones*
- *annealing at about 550°C helps in removing the residual stresses*
- *lateral faces parallel to 110 and 1-10 are preferred.*
- *lateral faces parallel to the 100, 010 cleavage should be avoided*
- *doping extremely difficult due to asymmetric Te – O covalent bonds*

4

Activator selection criteria

general
- luminescence properties of the free ion
- incorporation to the host lattice

particular
- only dopants having stable isotopes are acceptable
- unchanged thermal characteristics of doped crystals *(incorporation of uneven ions, avoided)*

no restriction on the emission spectrum and/or on the decay time of the activator

		At. Nb.	Electron config. of element	Oxi. No.	Coo. No.	ELR? (eV)	Fermi (eV)	Work func. (eV)	Ionic R (Å)	El. Neg. (V)	Chem. Hard.	Free ion emission (nm)	Stable isot. (%)	Dev. (%)
	Te	52	[Kr] $4d^{10} 5s^2 5p^4$	4	4	6.57	8.77	98.97	0.66	3.71	0.68		33.000	0.00
1	Mg	12	[Ne] $3s^2$	2	5				0.66			280 - 9900	100.000	0.00
	Mn	25	[Ar] [illegible] $4s^2$	2	6				0.66			284 - 350	100.000	0.00
2	Mn	25	[Ar] [illegible] $4s^2$	2	4				0.67	1.44	6.75		100.000	1.52
	Mn	25	[Ar] [illegible] $4s^2$	3	6	5.86	8.14	98.41	0.645	1.62	6.69	292 - 627	100.000	-2.27
3	Zr	40	[Kr] [illegible] $5s^2$	4	5				0.66			479 - 634	97.200	0.00
	Nb	41	[Kr] [illegible] $5s^1$	4	6	6.34	8.06	98.87	0.68			203 - 225	100.000	3.03
4	Nb	41	[Kr] [illegible] $5s^1$	5	6				0.64			-	100.000	-3.03
	Nb	41	[Kr] [illegible] $5s^1$	5	7				0.69				100.000	4.55

5

In order to avoid constitutional supercooling, doped crystals have to be grown under high thermal gradient with growth conditions similar to that of the high temperature solutions growth.

Growth parameters:

- axial gradient: 15-20 °C/cm
- pulling rate: 0.65-0.70 mm/h
- seed rotation: 26-28 rpm
- starting charge: 180g
- yield: 50-67 wt%

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Samples preparation

- *TeO_2 cleaves along the (100) and (010) planes. The 45 degree orientations of the cleavage planes at the edges favor the nucleation of minor cracks at the edges.*
- *Samples glued with melted wax (~70°C) were polished simultaneously with the help of "phantoms" of the same type of the crystal.*

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Work plan

1.	low temperature transmission	test the successful doping of TeO2, see if the scintillation characteristics may be improved
2.	steady state scintillation and TSL	
3.	low temperature photoluminescence	find the nature of luminescence in pure TeO2 ; study the TeO2:X luminescence characteristics
4.	check for traps existence at very low temperatures	further study of possible improvement of TeO2 scintillation characteristcs
5.	heat capacity	test the influence of doping on TeO2 thermal characteristics; possibly find correlation between thermal characteristics at low temperatures (mK) and other characteristics measurable at higher temperatures (LN?)

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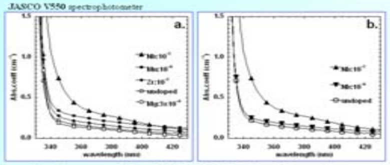
Transmission at RT

JASCO V550 spectrophotometer



a. Absorption spectra of undoped,Mg, Mn, Nb and Zr doped TeO_2 crystal
b. Absorption spectra of undoped, 10^{-4} and 10^{-3} mol/mol Nb doped TeO_2 crystals

- *Incorporation of Nb, Mn, Zr dopants is obvious.*
- *Mg incorporation is below precision limit.*

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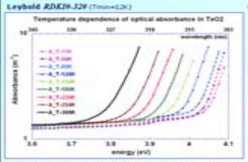
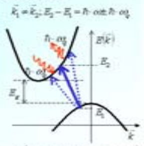
Transmission at low temperatures

Perkin Elmer *Lambda900*
Leybold *RDK10-320* (Tmin=12K)





indirect transitions:

$\vec{k}_1 = \vec{k}_2; E_2 - E_1 = \hbar \cdot \omega \pm \hbar \cdot \omega_q$

Typical behavior for indirect band transition

data analysis on the way

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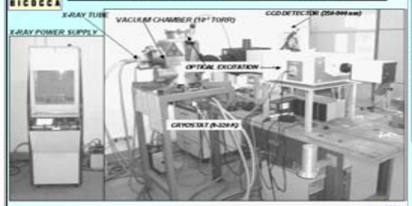
RADIO-PHOTO-THERMO LUMINESCENCE SET-UP



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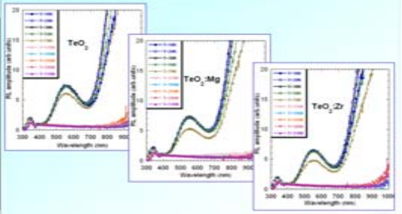
X ray excited steady-state luminescence



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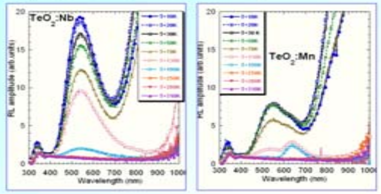

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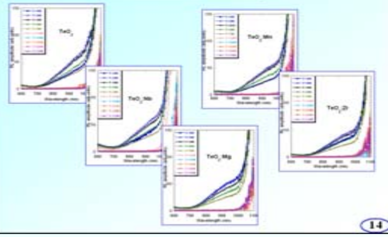

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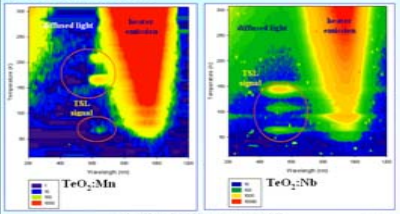
Termo-luminescence



after Xray (30 kV) exposure at 10 K

15

Conclusion and future plans

- *sucessful growth of doped TeO_2 crystals opens the possibility to realize a hybrid detector (scintillating bolometer) able to separate events due to radioactivity background thus enhancing substantially the sensitivity to neutrinoless DBD measurement.*
- *Mn and Nb doping seems a promissing way to enhance the scintillation light yield of TeO_2 crystals.*
- *low temperature photoluminescence measurements are forseen to find out the nature of scintillation centres*
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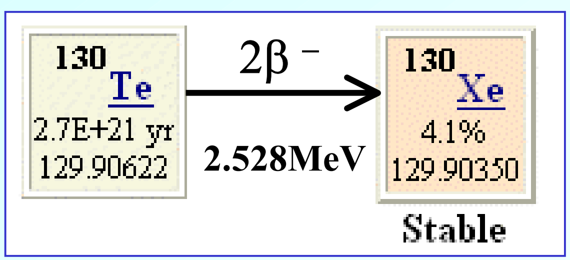

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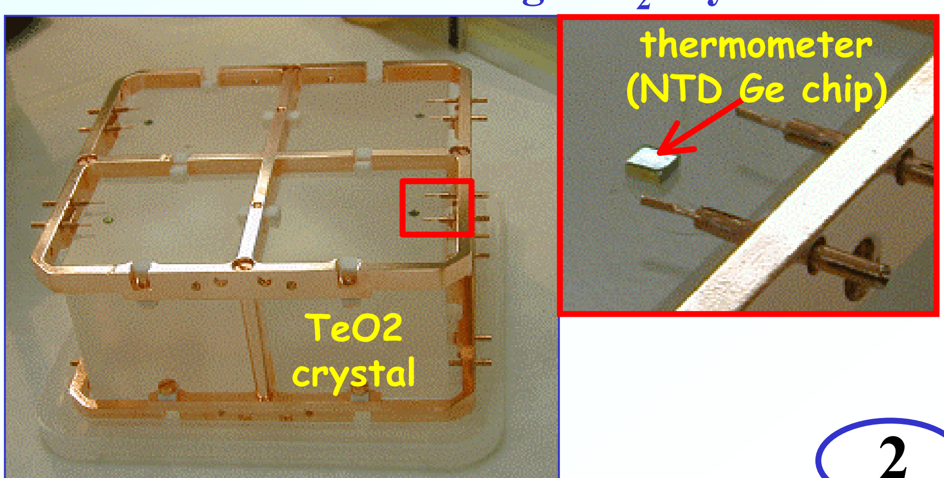

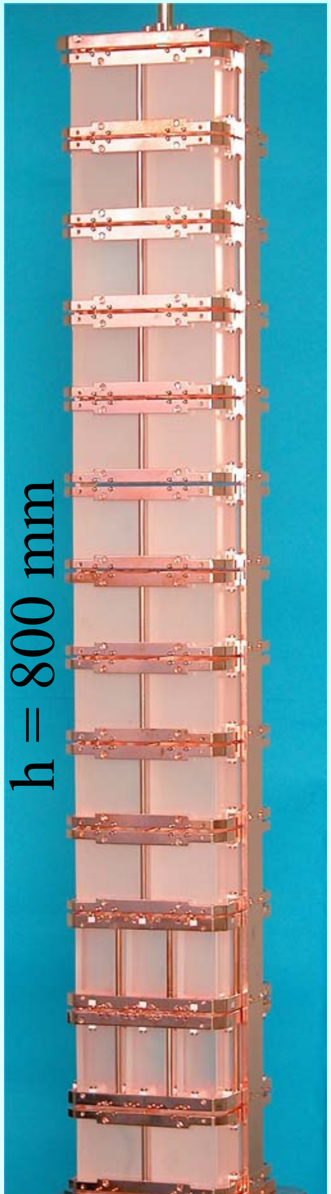

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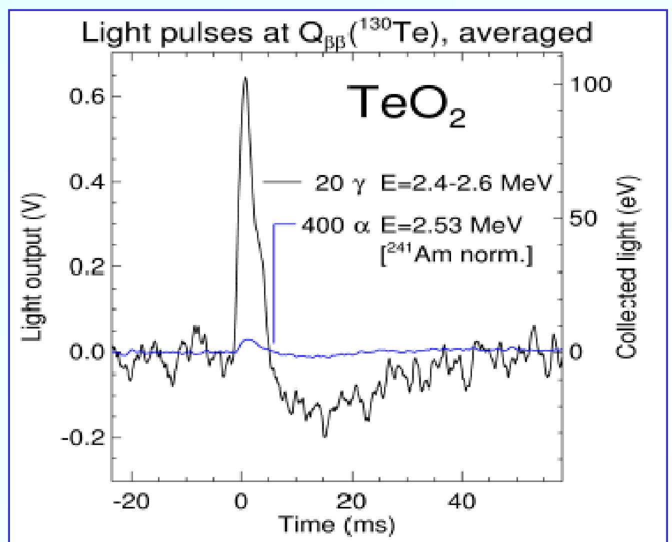

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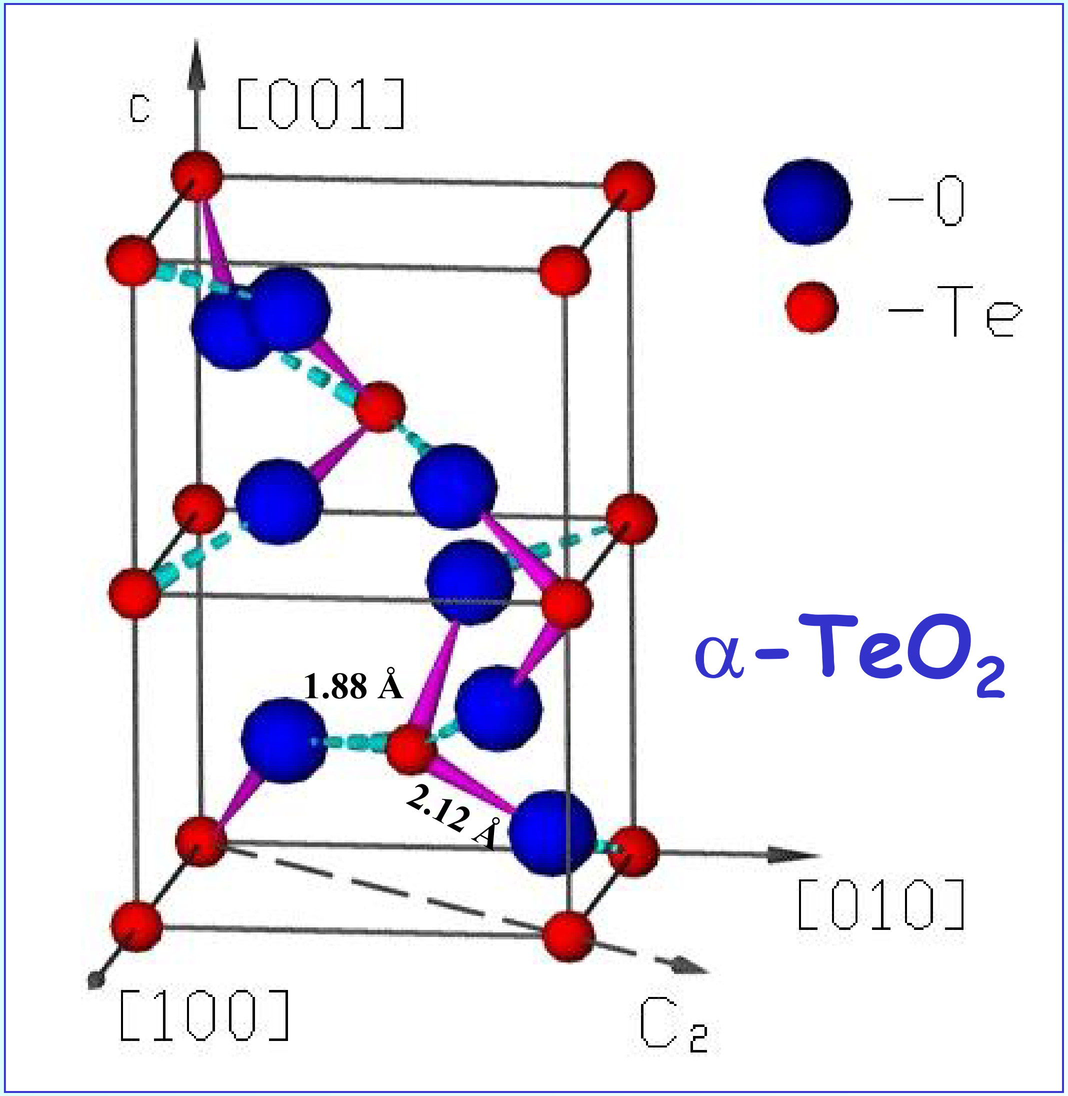

α-TeO$_2$

paratellurite

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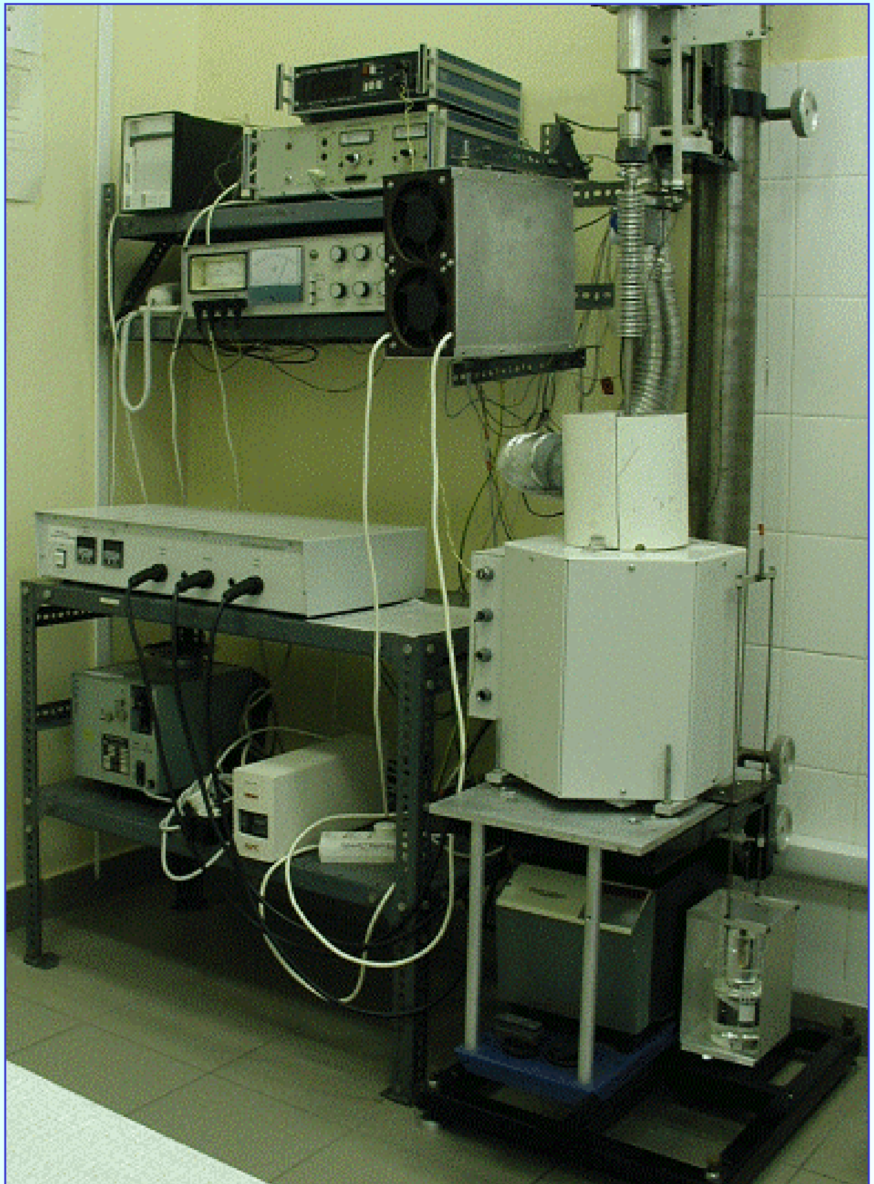

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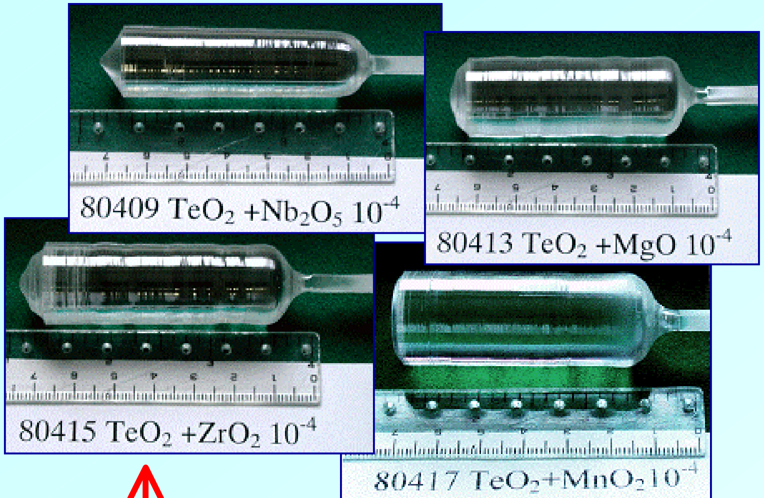

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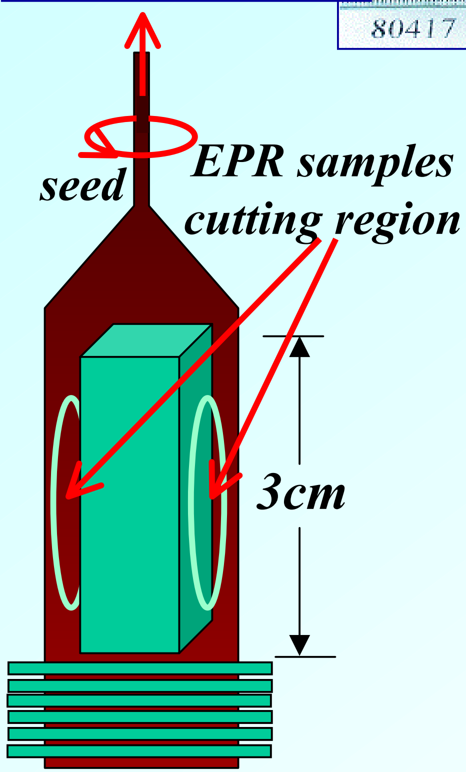

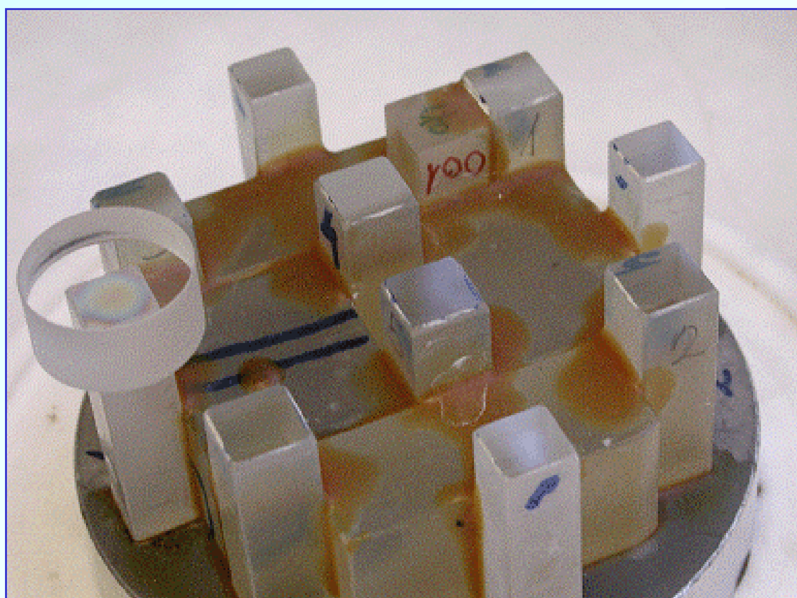

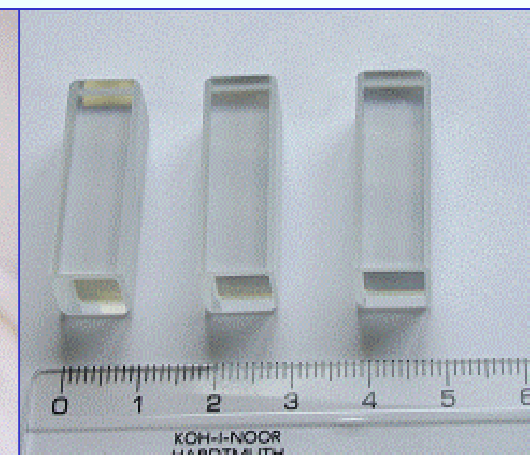

Work plan

1. low temperature transmission

2. steady state scintillation and TSL

→ test the successful doping of TeO_2, see if the scintillation characteristics may be improved

3. low temperature photoluminescence

→ find the nature of luminescence in pure TeO_2 ; study the TeO_2:X luminescence characteristics

4. check for traps existence at very low temperatures

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5. heat capacity

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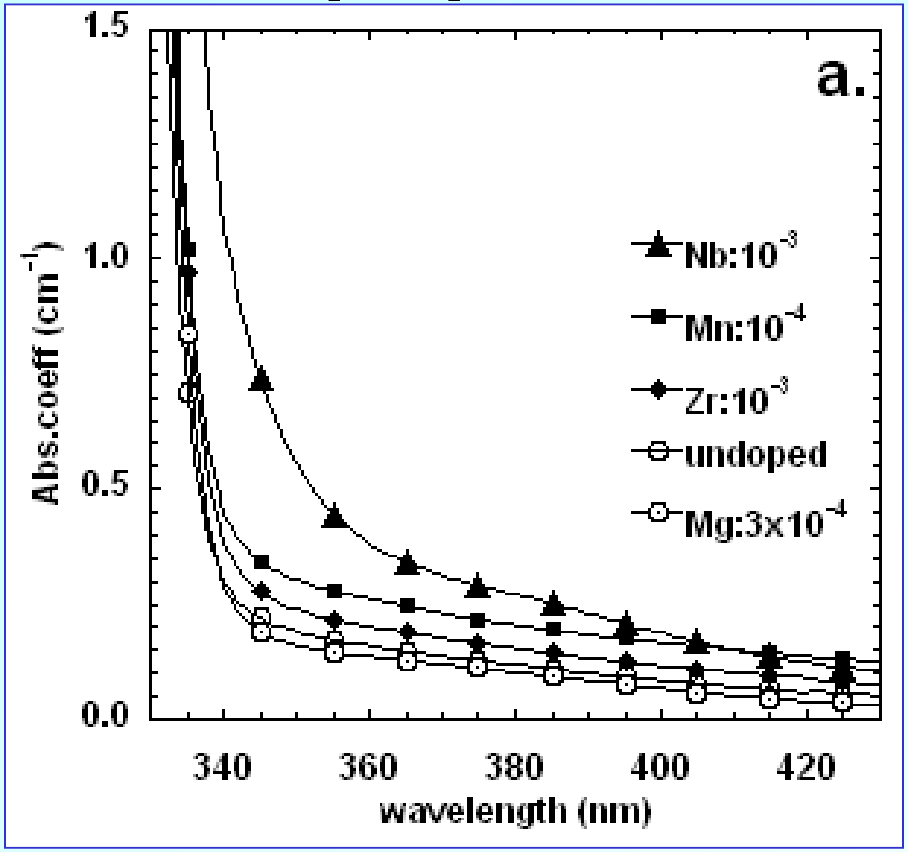
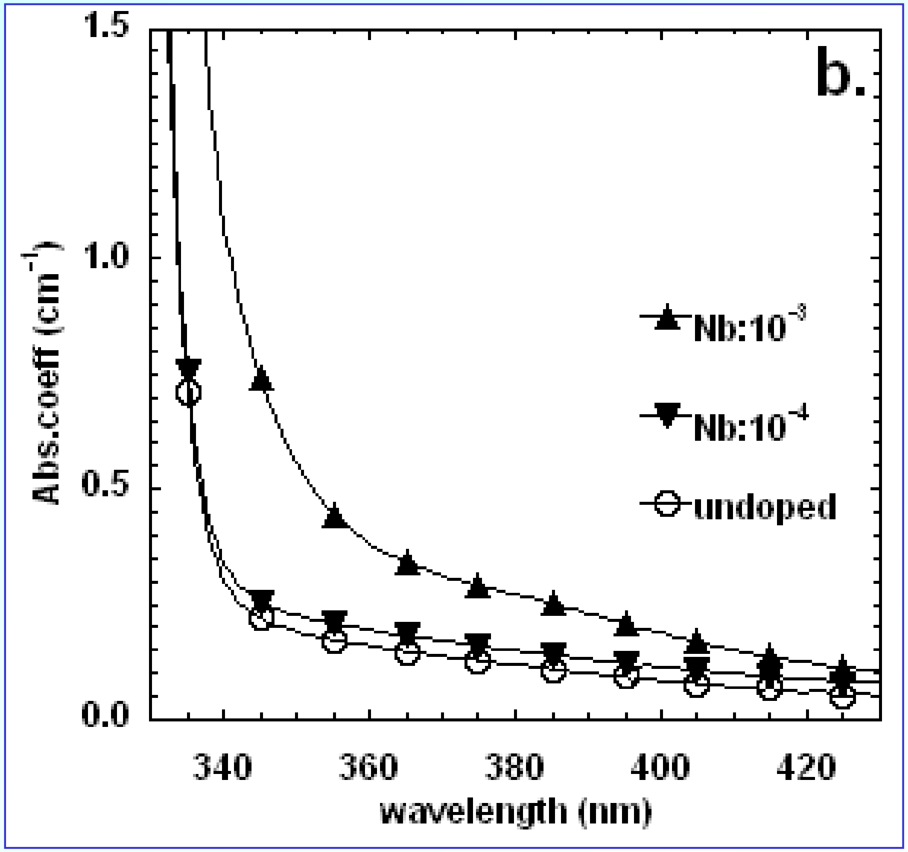
Transmission at RT

JASCO V550 spectrophotometer





a. Absorption spectra of undoped,Mg, Mn, Nb and Zr doped TeO_2 cystal
b. Absorption spectra of undoped, 10^{-4} and 10^{-3} mol/mol Nb doped TeO_2 cystals

- ***Incorporation of Nb, Mn, Zr dopants is obvious.***
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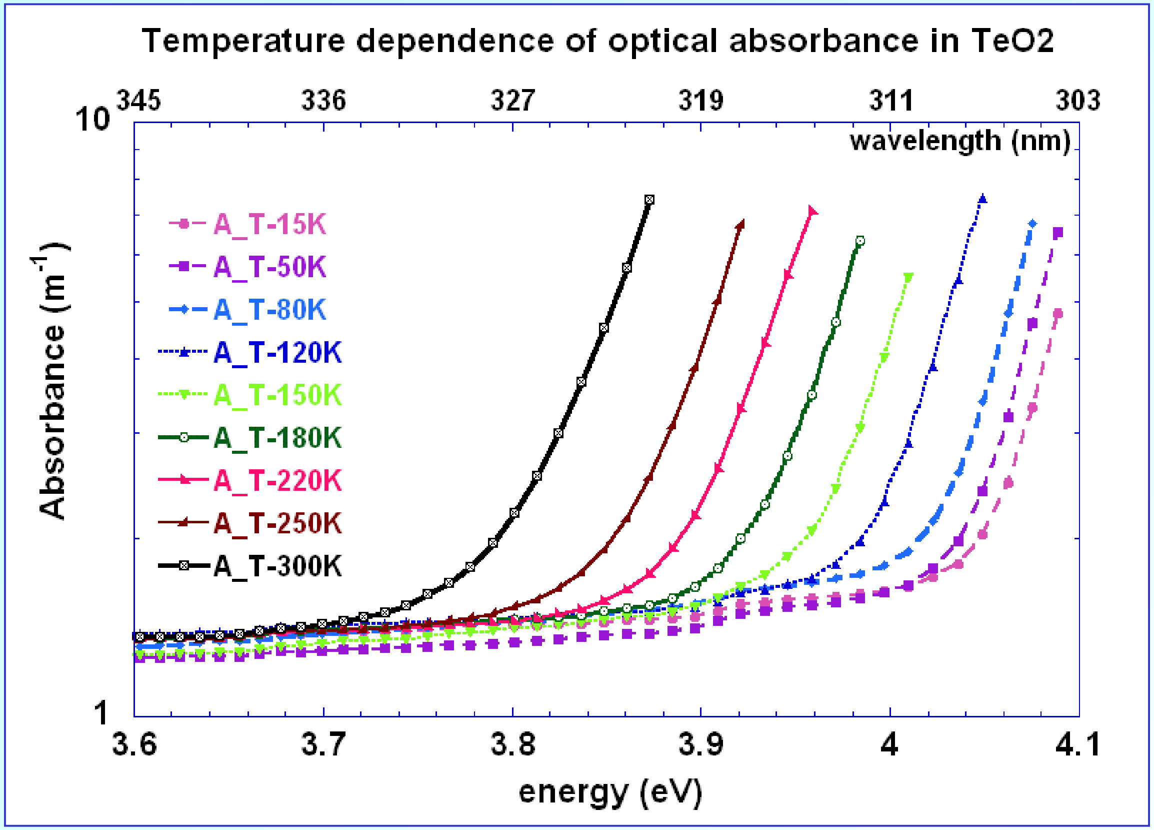
Transmission at low temperatures

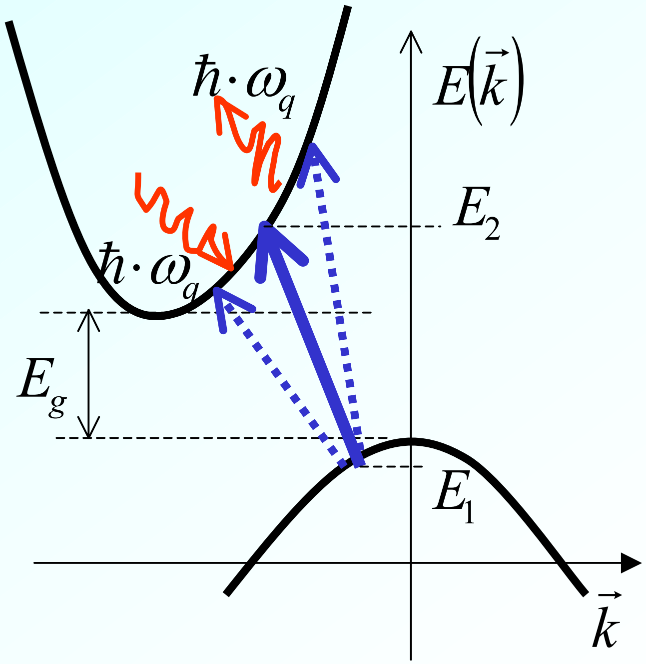
Perkin Elmer ***Lambda900***

Leybold ***RDK10-320*** (Tmin=12K)



indirect transitions:

$$\vec{k}_1 \neq \vec{k}_2; E_2 - E_1 = \hbar\cdot\omega \pm \hbar\cdot\omega_q$$



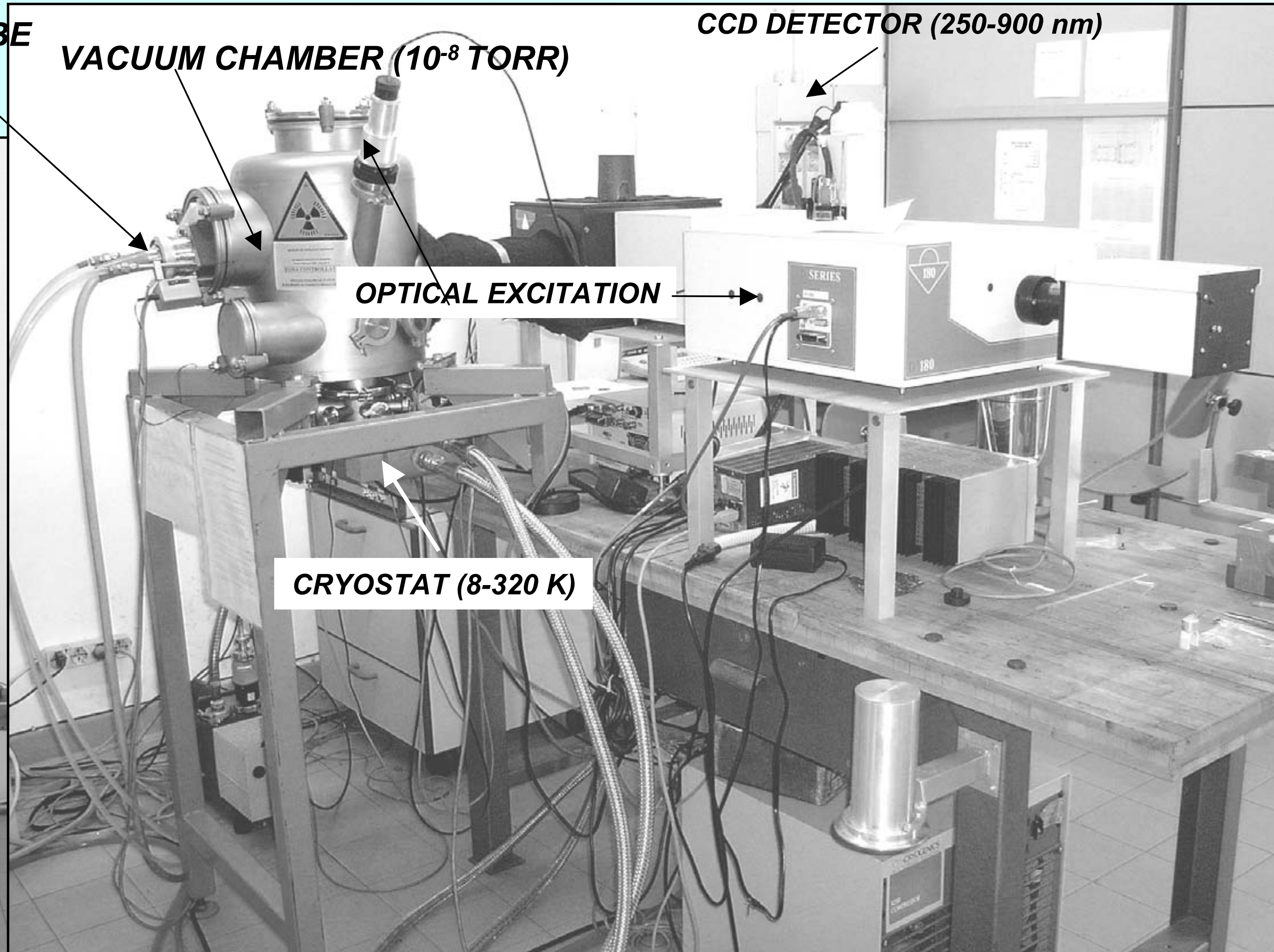
$$\alpha = \frac{const}{\hbar\cdot\omega}\cdot\left(\frac{(\hbar\cdot\omega - E_g + \hbar\cdot\omega_q)^2}{e^{\frac{\hbar\cdot\omega_q}{k\cdot T}} - 1} + \frac{(\hbar\cdot\omega - E_g - \hbar\cdot\omega_q)^2}{1 - e^{-\frac{\hbar\cdot\omega_q}{k\cdot T}}}\right)$$

Typical behavior for indirect band transition

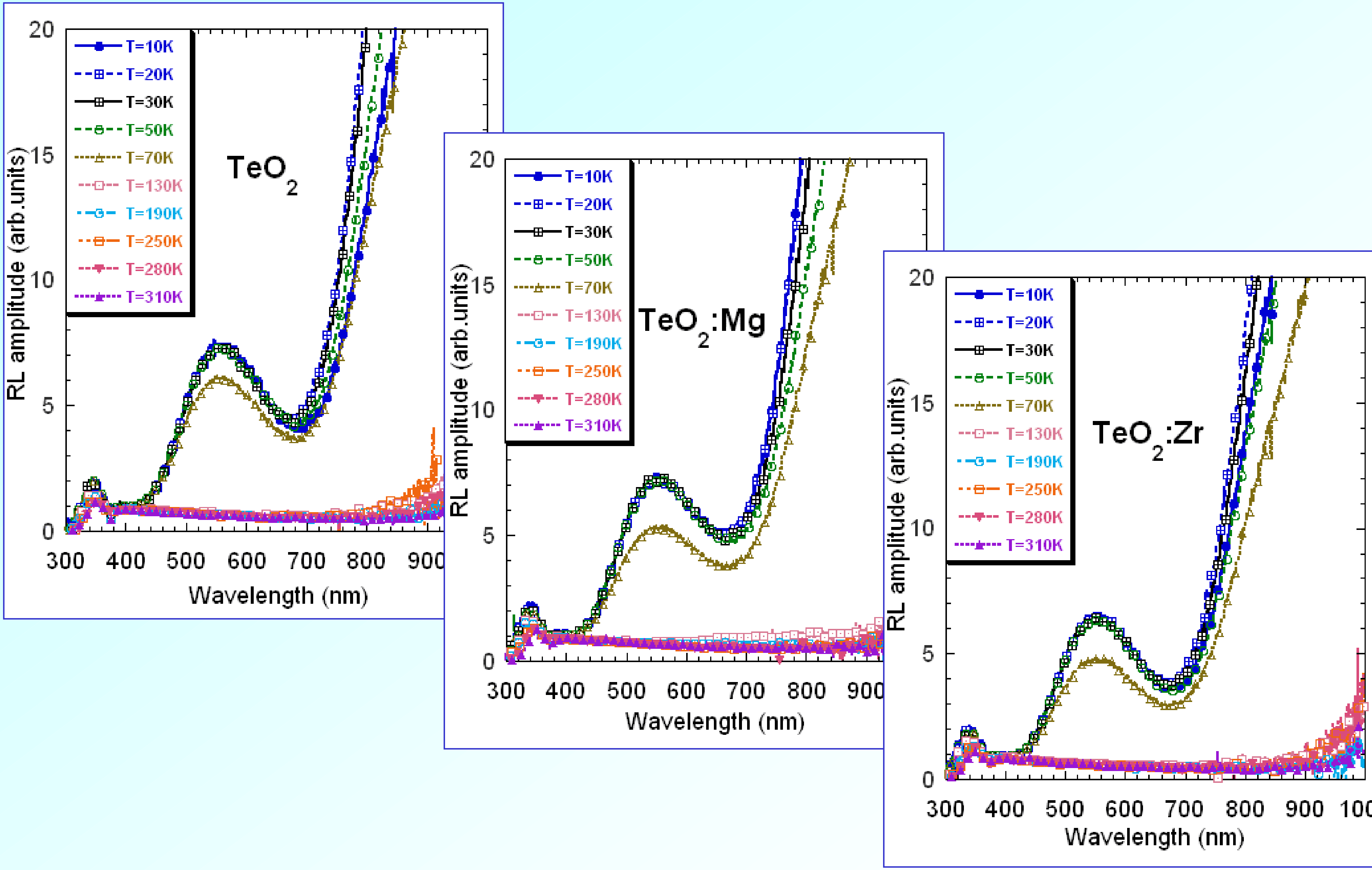
data analysis on the way

RADIO-PHOTO-THERMO LUMINESCENCE SET-UP

X-RAY POWER SUPPLY



X ray excited steady-state luminescence



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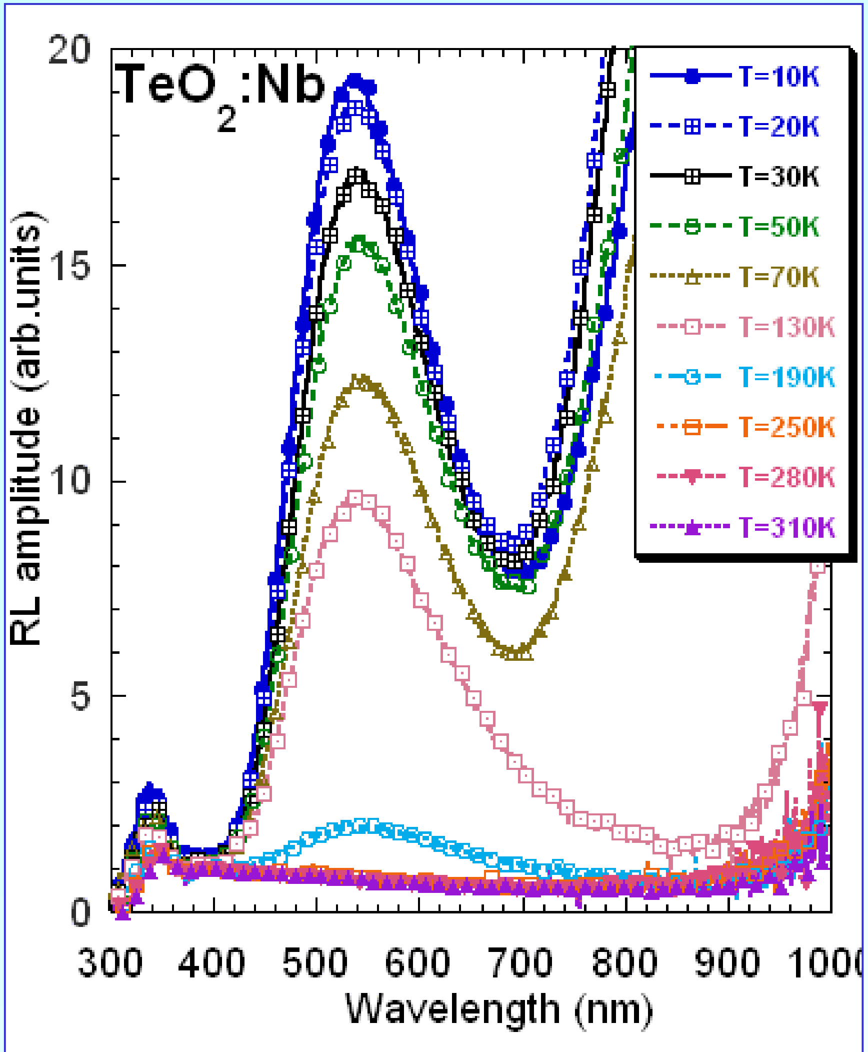

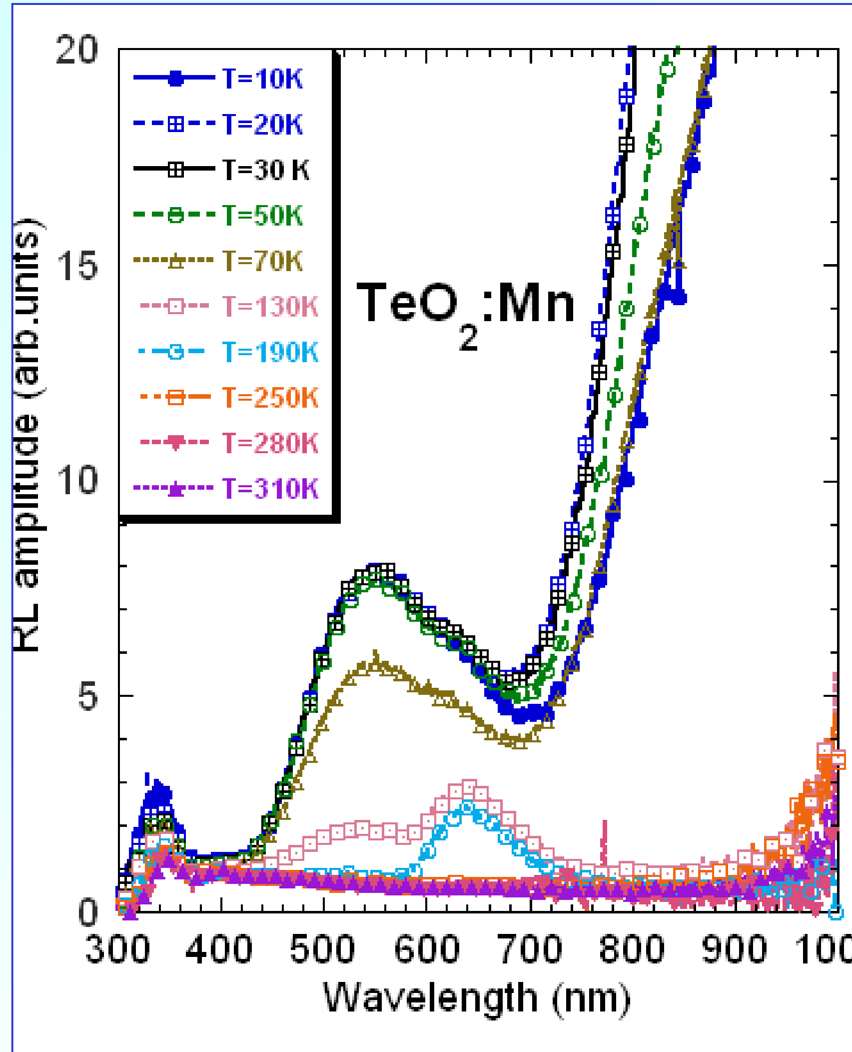

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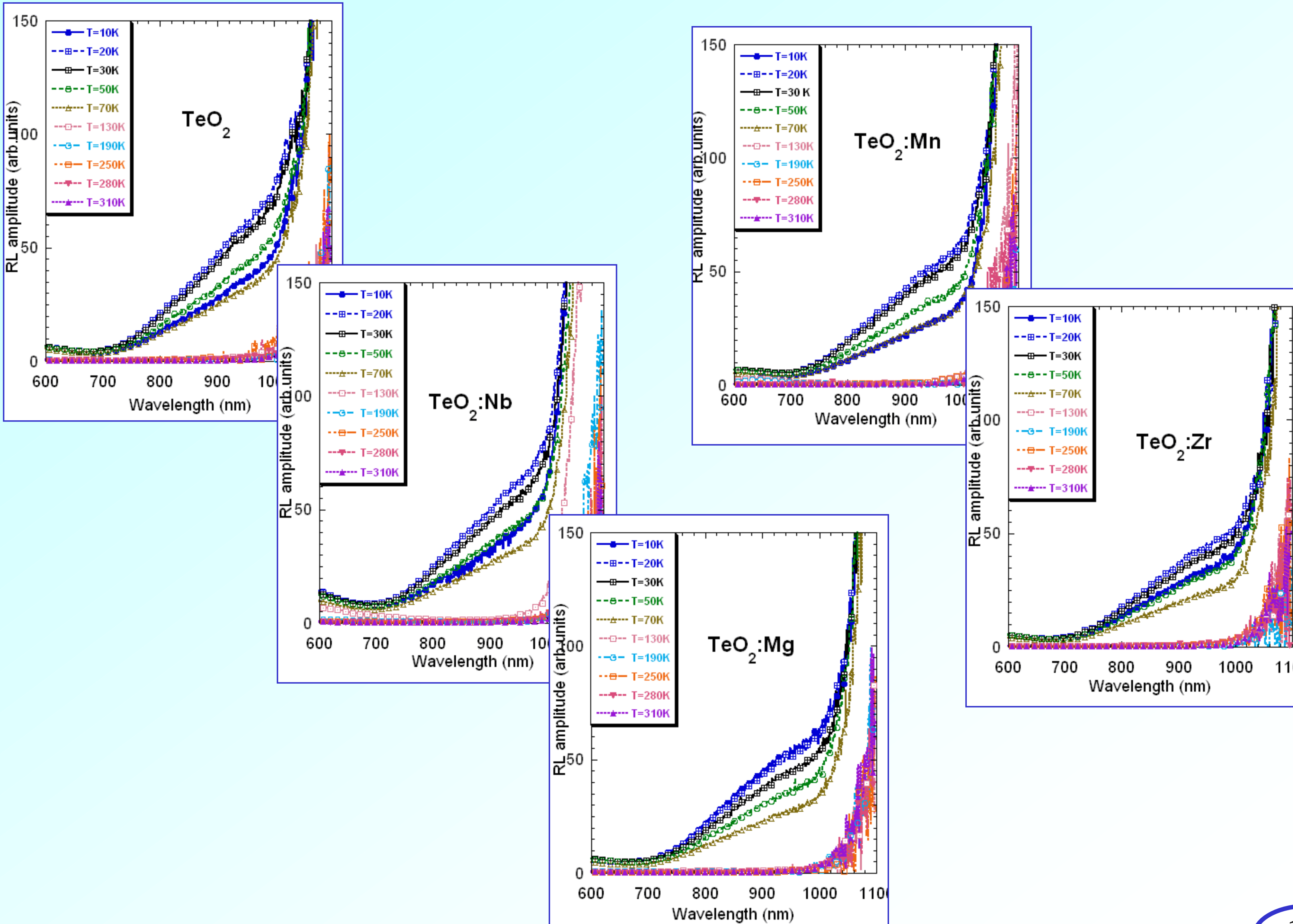
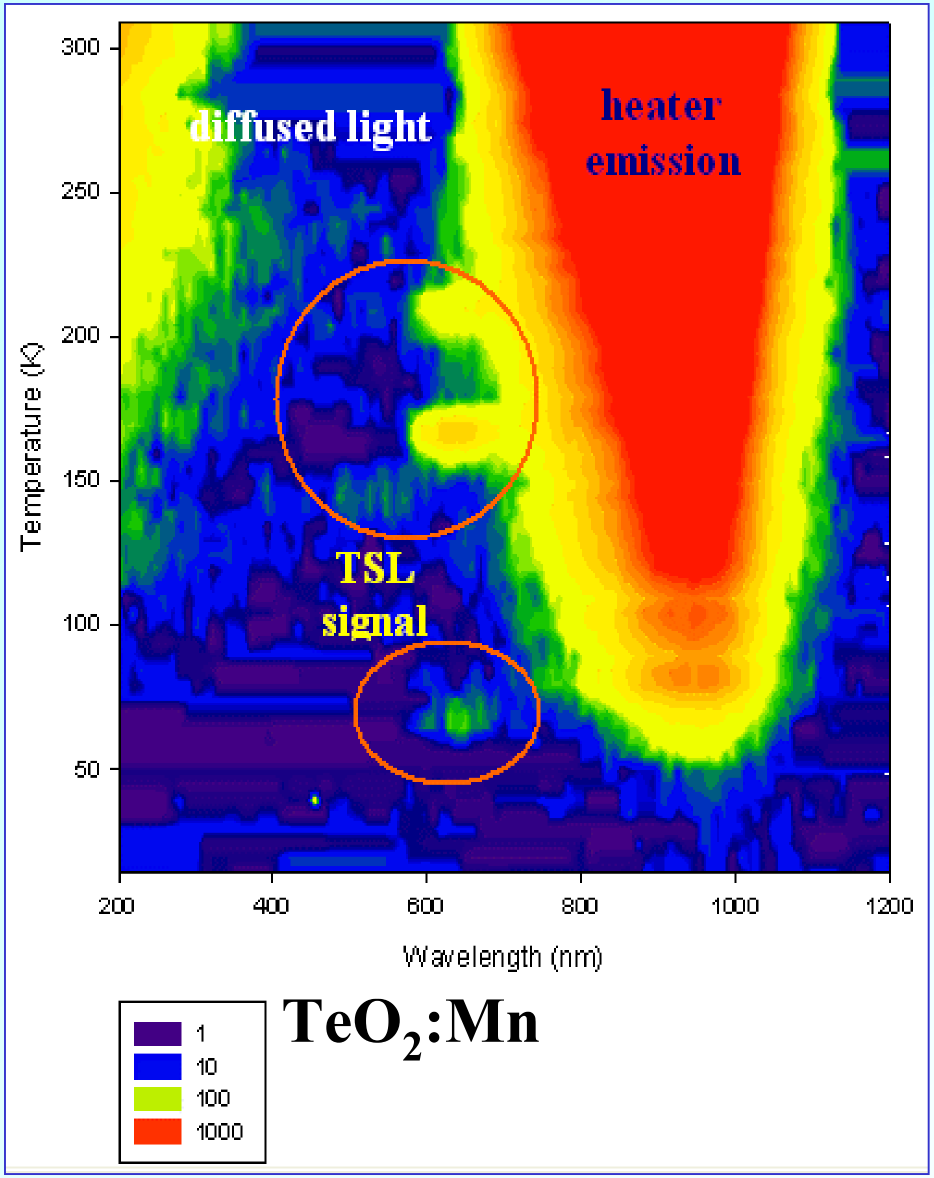
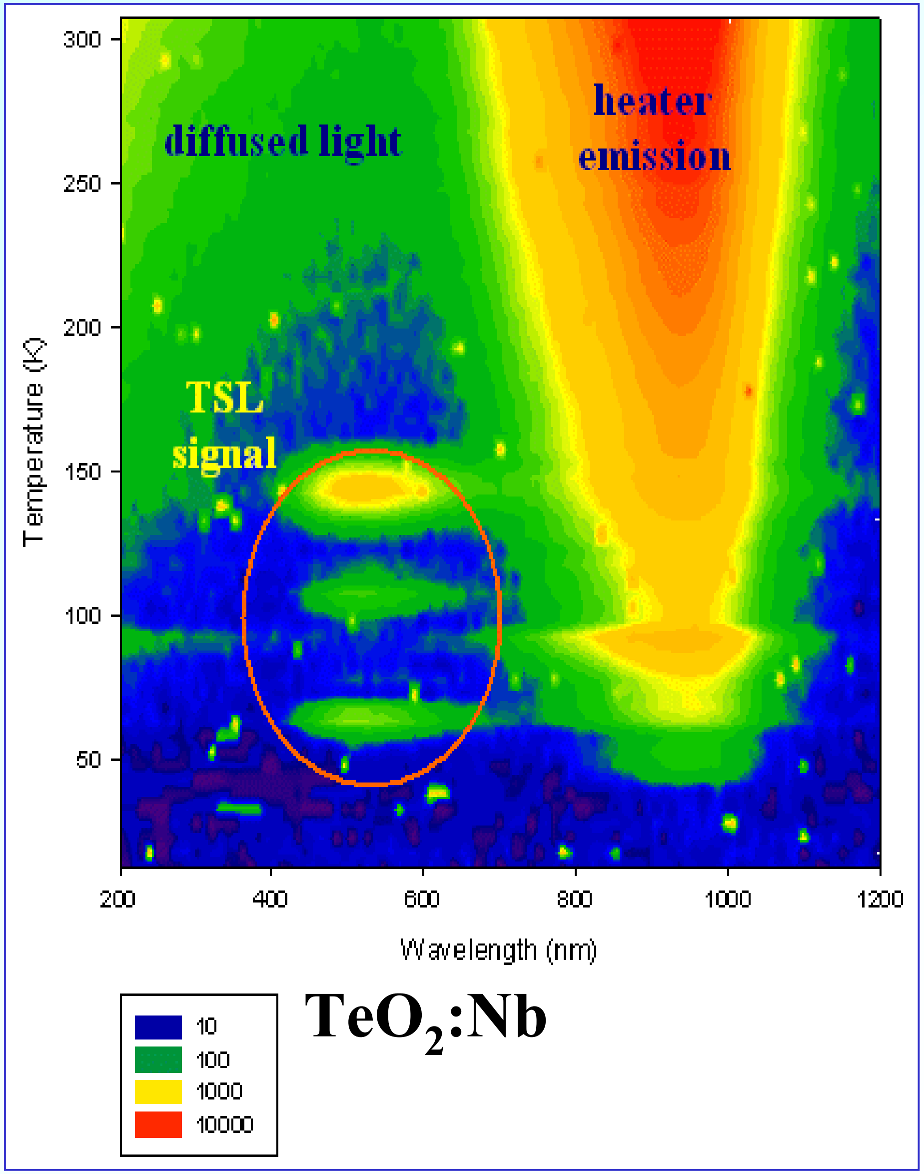


Thermo-luminescence





after Xray (30 kV) exposure at 10 K

Conclusion and future plans

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