

٦

AFOSR-TR- 91 0817

4

Luminescence and Electroluminescence Properties of Nd, Tm, Yb Doped GaAs and Some II-VI Compounds

Annual Report Submitted to:

The Air Force Office of Scientific Research

by:

Henryk J. Lozykowski Department of Electrical and Computer Engineering Stocker Center, Ohio University Athens, Ohio 45701-2979



91 RELS 052

REPORT DOCUMENTATION PAGE

Form Approved

REPORT DOC	OMB No. 0704-0188								
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching estimate of any other associate for any other associate for any other associate for information. Send comments regarding this burden estimate or any other associate for this collection of information, including suggestions for reducing this burden, is used as sources, collection of information, including suggestions for reducing this burden estimate or any other associate for information observations and Reports, 1215 Jefferson Dave Highway, Suite 1204, Arington, v4, 2202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC Jacob, 2015									
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 14 Aug. 1991	3. REPORT TYPE A	ND DATES COVERED						
4. TITLE AND SUBTITLE Luminescence and Ele Yb Doped GaAs and so	S. FUNDING NUMBERS AFOSR 90-0322A DEF								
& AUTHOR(S) Principle Investigat Professor DSc. Dr. H	TA 23051B1								
7. PERFORMING ORGANIZATION NAME Ohio University Office of Research a Athens, OH. 45701-29	UT 5473-1								
9. SPONSORING/MONITORING AGENCY AFOSR/PKD Building 410 Bolling AFB DC 20332	- 6448		10. SPONSORING / MONITORING AGENCY REPORT NUMBER						
			2306 B1						
123. DISTRIBUTION / AVAILABILITY STA	TEMENT	· ·							
U	nlimited								
13. ABSTRACT (Maximum 200 words)									
This report describes the luminescence and electron II-VI compounds. The pho PL spectra of CdS:Nd wer This indicates that in CdS:Yb at 9.3 K reveals broader line at 998.3 nm was observed for the fir well as at low temperat are assigned to tran- investigated as a funct dependence of the EL int a dominant one. Photo consist of sharp peaks indicate that the observed kinetics reveals the f through the Yb ³⁺ isoelec was observed for the firs 14. SUBJECT TERMS Photoluminescence,: E	e progress accomplish oluminescence proper toluminescence study re recorded and about CdS, Nd_{L}^{3+} occupies five sharp lines in a. Electroluminescent st time. Strong emiss ure revealing only sitions within the tion of voltage, to tensity shows that t oluminescence spectra related to Yb_{L}^{3+} rved emissions originant the tronic trap. Elect st time.	ties of Nd, Tm of GaAs:Yb sho t 20 sharp emis different symm the 985 nm - 9 the 985 nm - 9 the of ZnS:Tm emission was observ five groups of 4f shell of emperature and he direct impact a of InP:Yb a transition. The inate from one ation process of ric field quence Ce, Spectrosc	first year of research on a, Yb doped GaAs and some was no 4f emission. The sion lines were observed. etry sites. The PL of 990 nm range and a strong mbedded in a Boric matrix ed at room temperature as strong sharp lines which Tm_{4}^{3+} . EL intensity was frequency. The voltage t excitation mechanism is t different temperatures Time-resolved PL spectra Yb ³⁺ center. Rise time of the Yb ³⁺ is indirect thing of photoluminescence 15. NUMBER OF PAGES						
Polarization, GaAs, Rare Earth 17. SECURITY CLASSIFICATION [18.	SOME II-VI COMPO	unds doped wi	th 16. PRICE CODE						
OF REPORT	OF THIS PAGE	OF ABSTRACT							

TABLE OF CONTENTS

•

Introduction	1
Experimental	3
Photoluminescence & Electroluminescence	3
Polarization	3
Sample Preparation	4
Implantation	4
Annealing	6
Results and Discussion	8
Photoluminescence of GaAs:Yb, CdS:Nd, CdS:Yb	8
Electroluminescence of ZnS:Tm	11
Luminescence Properties of InP:Yb	14
References	17

Ac 2 - 8 11-24L $\mathcal{M}_{\mathcal{A}}$ yr i ÷., and the second Latification ŝŗ 5.4 er of blat Lux P# 2 Park \$ 4 7 c + Seven the service A-1 6- 40 S .:

LIST OF ILLUSTRATIONS

Figure Number

Page

1 a, b, c, d 2	
2 5	;
3 6	•
Table I 7	1
4	,
5)
6 1	0
7 1	1
8 A, B, C 1	3
9	5
10 A, B, C	5
11	6
12 1	6

PERSONNEL

Faculty

H. J. Lozykowski, Professor, Principal Investigator

Graduate Students

A. K. Alshawa, Ph. D. StudentZ. I. Akir, Ph. D. StudentT. Li, Ph. D. Student

SCIENTIFIC PAPERS

- The following scientific papers have been presented at the Ohio Section of the American Physical Society, Athens, Ohio, April 1991:
- 1. A. K. Alshawa and H. J. Lozykowski, "Electroluminescence of Tm doped ZnS".
- 2. H. J. Lozykowski, A. K. Alshawa, G. Pomrenke and I. Brown, "Luminescence Properties of Yb-Doped InP"
- The following scientific papers have been prepared for publication as a result of the research performed under Air Force sponsorship:
 - A. K. Alshawa and H. J. Lozykowski, "Electroluminescence of Tm doped ZnS", J. of Luminescence.
 - H. J. Lozykowski, A. K. Alshawa, G. Pomrenke and I. Brown, "Luminescence Properties of Yb-Doped InP", <u>J. of Applied Physics</u>.
 - 3. H. J. Lozykowski, T. Li, and Z. I. Akir, "A Very Sensitive Digital Spectropolarimeter and its Application to Optical Pumping Studies", J. of Applied Physics.

INTRODUCTION

In recent years the luminescence (PL and EL) properties of semiconducting materials such as Si, II-VI and III-V doped with rare earth ions have been studied intensively because of their potential application to light emitting devices. The emitted sharp lines with emission wavelengths insensitive to temperature variation results from RE^{3+} ion 4f transition.

The purpose of this research is to study the photoluminescence (electroluminescence) of GaAs doped with Nd³⁺, Tm³⁺, Yb³⁺, and some II-VI compounds (ZnS:Tm³⁺, CdS:Yb³⁺, CdS:Nd³⁺, ZnSe, ZnTe, and Cd_{1-x}Zn_xTe:Tm³⁺). In addition, we study InP:Yb because the luminescence spectrum of this crystal does not depend on the sample preparation method and the ytterbium ion has a simple spectrum because the Yb³⁺ 4f¹³ shell has only one excited state. The deep understanding of excitation mechanism in such a simple system can lead to better understanding of excitation mechanism in other more complicated RE³⁺ systems in semiconductors.

Figure 1a shows the energy levels scheme of the Nd³⁺ ion in cubic (T_d) and noncubic symmetry (C_{v3}, C_{v2}, C_s) environment. In cubic symmetry ${}^{4}F_{3/2}$ level is not split (Γ_{8} fourfold degenerated crystal field state). Therefore, in the cubic hosts, any splitting of the ${}^{4}F_{3/2}$ level is indicative for association of the Nd³⁺ ion with other defects. The same argument holds for the multiplicities of the ground state. The ground state ${}^{4}I_{9/2}$ in cubic symmetry is split into three states ($\Gamma_{8}, \Gamma_{8}, \Gamma_{7}$) and the first excited state ${}^{4}I_{11/2}$ into four crystal field states as in the left part of Fig. 1a. In noncubic symmetry, the fourfold degenerate Γ_{8} states of Nd³⁺ ion are split into two doublet each and the energy level structure is shown in the right part of Fig. 1a.

The emission spectra for the ${}^{4}F_{3/2} \rightarrow {}^{4}I_{9/2}$ transitions of Nd³⁺ in noncubic symmetry should exhibit all ten transitions. At low temperature, when only the lower level of ${}^{4}F_{3/2}$ is occupied, only 5 lines should be observed in luminescence emission. In absorption at low temperature such that only the lowest component of ${}^{4}I_{9/2}$ state is occupied, only two lines should be observed. In Fig. 1b we show the possible absorption and emission transition with wavelength (in µm) for Nd³⁺ in cubic symmetry in semiconductors with band gap $E_{g} \ge 2.14 \text{ eV}$. Figure 1c shows energy level schemes for Yb³⁺ ion in cubic (T_d) and noncubic symmetry, and the luminescence transition for Tm³⁺ ion in ZnS is shown in Fig. 1d.



Figure 1 a,b,c,d

EXPERIMENTAL

Photoluminescence & Electroluminescence

The photoluminescence measurements were carried out using a Laser Ionic Model 553A Ar⁺ laser as the excitation source. A Spectra Physics Model 3900 CW Ti:Sapphire laser was used for excitation spectra. For time-resolved spectra and time measurements, the pulsed excitation was obtained by an IntraAction Model AOM-125 acousto-optic light modulator with rise and fall times around 2 nsec. The drive power for the light modulator was provided by an IntraAction Model ME-125 signal processor. The pulsed excitation was detected by an Antel Model AR-S2 picosecond photodetector and monitored on an HP Model 54503A 500 MHz digital oscilloscope. In electroluminescence experiments, a sinusoidal signal generator and a DC power supply were used to perform total emission measurements. For pulsed excitation EL, an AVTECH Model AVR-4B-C pulse generator was used. The samples were mounted on a cold finger cooled by a closed-cycle helium cryostat down to 8.5 K.

The emission was dispersed by a Jarrel Ash Model 78-490 0.75m scanning monochromator equipped with a 1180 grooves/mm grating. The signal was detected by photomultipliers Hamamatsu R632-01 and R925 with spectral response in the range of 400-1200 nm and 400-930 nm, resepectively. The second photomultiplier was also used to detect the pulsed excitation signal in the PL time measurements. The signal from the photomultiplier is passed through a fast ORTEC 474 preamplifier to a dual channel gated photon counter Model SR-400. Finally, the output signal is transferred to a computer for analysis and plotting.

Polarization

For photoluminescence (electroluminescence) polarization measurements we modified our digital spectropolarimeter to operate at the spectral range from 450 nm to 2000 nm (in digital mode the range from 450 nm to 1200 nm is limited by the photomultiplier spectral response.) The modified optical range was accomplished utilizing Oriel Fresnel rhomb achromatic retarders. The quarter wave or the half wave achromatic retarders are in series with a Glan-Thompson crystal polarizer in the excitation channel to provide $90^{\circ} \pm 2^{\circ}$ (σ + or σ -) or $180^{\circ} \pm 2^{\circ}$ (linear polarization)

phase retardation. The heart of the setup consists of a photo-elastic modulator (PEM-80) and a dual channel gated photon counter which has the capability to compensate the variation of excitation intensity with time and wavelength. The second important modification is automatic wavelength tracking of the modulator to insure the constant retardation phase ($\pi/2$ or $\pi/4$) when the wavelength of the analyzed light is scanned in wide range. The angular aperture of PEM-80 modulator comprises a 50 degree full-cone angle.

Unlike the conventional lock-in or other analog systems, where the difference of two oppositely polarized light components (AC) and the average of these components (DC) are extracted electronically, and the ratio AC/DC is recorded as degree of polarization, our setup directly records the σ + and σ - components (or, in the case of linear polarization, I_{\parallel} and I_{\perp} components) of the light signal in the same run (of wavelength, temperature, etc.) The block diagram of the instrument for the measurement of the degree of circular or linear polarization of luminescence light and excitation polarization spectroscopy is shown in Fig. 2. A detailed description of the spectropolarimeter system is under final preparation for publication.

Sample Preparation

Implantation

The ion implantation of rare earth was done by Dr. I. G. Brown from Lawrence Berkeley Laboratory at the University of California, Berkeley (because of technical problems, we received the samples at the end of May 1991.) Implantation of Nd, Yb, and Tm was performed with an unconventional implantation technique using a new kind of high current metal ion source developed at Berkeley by Dr. Brown et al. This MEtal Vapor Vacuum Arc (MEVVA) ion source makes use of a dense metal plasma generated directly from the metal cathode material as the medium from which ions are extracted. The source is repetitively pulsed and the implantation is done on a broad beam mode, with a d rect line -of-sight from the ion source to the target. High current beams of a wide range of multiply-charged metal ions can be produced. Beam extraction voltage is up to 100 kV, for a mean ion energy of up to several hundreds of keV by virtue of a mean ion charge state that is typically 2 to 3. The beam current can be up to several amperes peak and around 10 mA time averaged delivered onto target. The source has been operated with virtually all of the solid metals of the periodic table. The high energy implants of 1 MeV



Figure 2 Block diagram of the spectropolarimeter

(sample 15) were performed at Universal Energy Systems (UES), Dayton, OH. The list of III-V and II-IV semiconductor compounds, their implantation parameters and post implantation annealing conditions is summarized in Table I.

• Annealing

The samples were cut to small pieces (4 mm x 4 mm squares) and then cleaned by standard methods. Thermal heat-pulse using a strip heater was used to anneal the samples up to 900° C for 10-15 sec. The annealing process was performed using the apparatus shown in Fig.3 which we designed and built in our laboratory. A flat graphite plate of \approx 3mm thickness is placed on the tantalum strip heater. The samples are placed face down on the graphite plate and covered with a thin graphite lid of \approx 1mm thickness. The temperature is measured and monitored by OMEGA Model 650 microprocessor controlled temperature indicator through a thermocouple placed inside the graphite plate. The variation of annealing temperature with time is recorded by an x-y recorder as shown in the inserts of Fig. 3. The rise time of the temperature was controlled by the AC voltage applied to the strip heater. For temperatures up to 900° C, our system maintains a rise time of 6 sec and a decay time from 900°C to 500°C of 22 sec.



Figure 3 Thermal-Heat-Pulse Annealing System

			Implantation			Anneal		
	Sample	Substrate (type)	ion	Encrgy (KcV)	Dosage (cm ⁻²)	Temp. (C°)	Time (sec)	Gas
1	GaAs	(SI, p, n)*	YЪ	140	7.5x10 ¹³	900	10	fg
2	GaAs	(SI, p, n)*	Nd	150	7.5x10 ¹³	900	10	fg
3	GaAs	(SI, p, n)*	Tm	145	7.5×10 ¹³	900	10	fg
4	ZnSe	GaAs** (p)	Yъ	140	7.5x10 ¹³	450	15	fg
5	ZnSe	GaAs:Cr (SI)	Tm	145	7.5x10 ¹³	600	15	fg
6	ZnTe	GaSb	Yb	140	7.5x10 ¹³	400	15	fg
7	ZnTe	GaAs:Cr (SI)	Nd	150	7.5×10 ¹³	900	15	fg
8	Cd _{1-x} Zn _x Te	(***)	Tm	145	7.5x10 ¹³	900	15	fg
9	ZnS	Si (100)	Tm	145	7.5x10 ¹³	N/A	N/A	N/A
10	ZnS	Si (100)	Nd	150	7.5×10 ¹³	N/A	N/A	N/A
11	ZnS	Si (100)	Yb	145	7.5x10 ¹³	N/A	N/A	N/A
12	CdS	-	Tm	145	7.5x10 ¹³	900	15	fg
13	CdS	•	YЪ	140	7.5x10 ¹³	900	15	fg
14	CdS	-	Nd	150	7.5x10 ¹³	900	15	fg
15	InP	InP:Fe (SI)	Yb	1000	3×10 ¹³	650	15 min	fg
16	InP	InP:Fe (SI)	УЪ	140	5-10×10 ¹³	600	10 min	fg
17	InP	InP:Fe (SI)	Yb	140	5-10x10 ¹³	680	10 min	fg

Table I

SI: Semi-insulating Cr-doped $(0.1-2\times10^{16} \text{ cm}^{-3})$ GaAs p: p-type Zn-doped (p=1×10¹⁷ cm⁻³) GaAs n: n-type Si-doped (n=1×10¹⁸ cm⁻³) GaAs *

p-type Be-doped GaAs epilayer on a p^{*}-type Zn-doped GaAs **

*** Three samples with three different Zn concentration, x, 10%, 22%, and 31%

RESULTS AND DISCUSSION

Photoluminescence of GaAs: Yb, CdS:Nd, CdS: Yb

The photoluminescence (PL) study was performed only on some of the samples listed in table I because we received the samples from implantation at the end of May 1991, and we are still waiting for cooled Germanium infrared detectors EO-817P and EO-817S from North Cost Optical Systems and Sensors.

The PL study of GaAs implanted with Yb^{3+} ions shows no 4f intracenter emission. Similar results was reported by G. S. Pomrenke et al and K. Takahei et al on MOCVD-grown Yb doped GaAs despite the Yb incorporation being confirmed by SIMS. The absence of 4f Yb³⁺ emission in GaAs is unknown and required more investigations. The direct excitation of Yb³⁺ ions by photons, impact excitation in high electric field, or by electron beam excitation will give the answer for the question: are the incorporated Yb³⁺ ions optically active in GaAs or not? This type of experiment is planned in the near future in our laboratory.

Figure 4 shows the characteristic sharp emission spectra of Nd³⁺ implanted CdS and rapid thermal annealed (RTA) at 900°C for 15 sec in forming gas. The excitation was performed using a 488 nm Ar⁺ ion line at 9.3 K. The observed emission lines are due to ${}^{4}F_{3/2} \rightarrow {}^{4}I_{9/2}$ transitions of Nd³⁺ ions in noncubic symmetry. At temperature 9.3 K, only the lower level of ${}^{4}F_{3/2}$ is occupied, and we should observe only 5 lines in luminescence emission (Fig. 1a left). Our spectrum shows about 20 lines. This observation indicates that in CdS, Nd³⁺ ions occupied different symmetry sites. The preliminary kinetics study of decay of emission lines at 898.7 nm and 903 nm shows decay times 340 µs and 318 µs, respectively.

The EPR study (Watts et al) shows that isolated RE^{3+} ions are found to be substitutional for the metal ion in zinc blende (ZB) crystals. Spectra of RE^{3+} ions in wartzite (W) lattices are coming from three types of sites: (1) the RE^{3+} ions form several types of associates with chargecompensating ions; (2) the substitutional RE^{3+} ions with no local charge compensation (the possibility of a compensating defect along the C-axis cannot be excluded); (3) another axial and orthorhombic spectrum are observed. Identification of observed emission centers required additional investigation such as time-resolved, polarization and excitation spectroscopy which are in progress in our laboratory.







Figure 5



Figure 6

As seen in Fig. 5, for CdS:Yb the characteristic sharp RE emission lines were observed at a spectral range from 895 nm - 1010 nm for transitions between the crystal field split spin orbit level ${}^{2}F_{5/2} \rightarrow {}^{2}F_{7/2}$ of Yb³⁺ (4f¹³5s²5p⁶). The emission spectrum contained five sharp lines in the wavelength region of 985 nm - 990 nm and a strong broader line at 998.3 nm with broad, not well resolved peaks between the 990 nm - 1020 nm region. Figure 6 shows the temperature dependence of ${}^{2}F_{5/2} \rightarrow {}^{2}F_{7/2}$ emission lines. The emission intensities increased as temperature increased from 8.5 K until they reached their maximum value at about 30 K, then they started to decrease with further increases of temperature. At a temperature of 60 K, the sharp emission lines in the 985 nm -990 nm region are temperature broadened and merged and become unresolved at higher temperatures.

Electroluminescence of ZnS:Tm

The electroluminescence of thulium doped ZnS embedded in boric matrix, silicon rubber and some organic binders was investigated in comparison to photoluminescence. The power efficiency of the ZnS:Tm was determined under cathode-ray excitation as 0.216 W/W, the highest yet reported for any rare-earth-activated phosphor. The EL cell was prepared using transparent conducting glass $(In_{0.9}Sn_{0.1}O_2)$ as shown in Fig.7. The Electroluminescence spectra were investigated as a function of temperature, voltage and frequency. The emission spectra show only strong sharp emission lines which are assigned to transitions within the 4f shell of Tm³⁺. The



Figure 7 The ZnS:Tm Electroluminescence Cell

emission spectra revealed five groups of lines at 483 nm (transitions ${}^{1}G_{4} \rightarrow {}^{3}H_{6}$), 662 nm (transitions ${}^{1}G_{4} \rightarrow {}^{3}H_{4}$), 711 nm (transitions ${}^{3}F_{3} \rightarrow {}^{3}H_{6}$), 785 nm (transitions ${}^{1}G_{4} \rightarrow {}^{3}H_{5}$) and 806 nm (transitions ${}^{3}F_{4} \rightarrow {}^{3}H_{6}$). Strong emission was observed at room temperature as well as low temperature. The voltage dependance of the EL intensity and kinetics were studied under sinusoidal, pulsed and DC excitations. The temperature dependence of the emission intensity was investigated in the range of 8.5 K-290 K, as shown in Fig. 8 A, B, C. The emission around 483 nm and 660 nm decreased as the temperature increased. The emission intensities around 805 nm increased with temperature increase until they reached their maximum value at 210 K, then they started to decrease with a further increase in temperature. However, a strong sharp peak at 805 nm can still be observed at room temperature. The voltage dependence of the EL intensity and the kinetics were studied under sinusoidal, pulsed and DC excitation. Analysis of the emission intensity and the kinetics were studied under sinusoidal, pulsed and DC excitation. Strong

DC EL was observed at room temperature at a low voltage of 38 V. The investigation of the emission intensity as a function of frequency was performed in the frequency range of 1-16 KHz. The intensities of all lines increased to a maximum at 7 KHz and then decreased by a further increase in the excitation frequency. A detailed discussion on electroluminescence of ZnS:Tm is under final preparation for publication.



Figure 8 A, B, C

Luminescence Properties of InP:Yb

The photoluminescence of Yb-implanted InP was investigated under CW and pulsed excitation using Ar⁺ ion laser. Figure 9 shows the PL spectra of the different samples of InP:Yb listed in Table I. The spectra consist of a sharp peak at 1001 nm and two broader peaks at 1005.5 nm and 1007 nm (transitions ${}^{2}F_{5/2} \rightarrow {}^{2}F_{7/2}$). The time-resolved PL spectra were recorded for the three samples as shown in Fig.10 The intensities of all emission lines decreased uniformly with increasing the time delay after excitation. This indicates that the emission originates from the same Yb³⁺ center. The study of the rise time and decay time processes (intrinsic excitation) shows that the rise time (9.3 μ s) is smaller than the decay time (11.7 μ s). This reflects the fact that the excitation process of the Yb^{3+} is indirect through the Yb^{3+} isoelectronic trap (the isoelectronic trap model was proposed by Witney et al). By assuming the isoelectronic trap model, the kinetics study shows that if the excess electron relaxation time is much shorter than the center-filling relaxation time, the RE³⁺ luminescence response to a square pulse excitation will be exponential assuming uniform excitation. This is fulfilled in our case because of the small thickness of the Yb³⁺ implanted layer (≈ 300 nm). The rise of the luminescence intensity is an exponential function with a time constant that depends on the excitation intensity. For generation rate (excitation intensity) the rise time will be the capture electron lifetime on the RE isoelectronic trap. Therefore, with increasing the excitation intensity, the rise time will decrease which is confirmed by our experimental results. PL excitation spectra for the three emission lines of 1000.1 nm, 1005.5 nm, and 1007 nm were recorded using a tunable Ti:Sapphire laser. No emission is observed for excitation below the band gap due to the very small thickness of the Yb-implanted layer. The temperature dependence of InP:Yb was investigated in the 9K - 100K range. From Fig. 11 we can see that the intensities of all emission lines decreased when increasing the temperature. We studied the effect of the electric field on the PL of InP:Yb. To perform this experiment, a semi-transparent gold electrode (100Å) was evaporated on the implanted surface of InP and a second thick gold electrode (500Å) was deposited on the opposite side of the sample. Figure 12 shows the quenching of PL of Yb³⁺ emission as a function of the electric field. The insert of Fig. 12 shows the electric field in the surface layer under the semi-transparent gold electrode. Assuming the uniform absorption coefficient of 10⁵ cm⁻¹ for InP at 9 K, 95% of the excitation photons are absorbed within 300 nm of the surface layer where a strong electric field exists. The quenching of PL of Yb³⁺ can be explained by two possible mechanisms: (1) exciton bound to the isoelectronic

trap disassociation by hot electron impact ionization or (2) swept of electrons or holes to the Au-InP interface where they will recombine nonradiatively. The electric field quenching of photoluminescence presented in Fig. 12 needs more investigations to exclude the possibility of temperature quenching.



Figure 9





Figure 10 B

Figure 10 C



Figure 11



Figure 12

REFERENCES

- I. G. Brown, J. E. Galvin, and R. A. MacGill, Appl. Phys. Lett. 47, 358 (1985).
- I. G. Brown, J. E. Galvin, B. F. Gavin, and R. A. MacGill, Rev. <u>Sci. Instrum. 57</u>, 1069 (1986).
- R. K. Watts and W. C. Holton, <u>Phys. Rev., 173</u>, 417 (1968).
- G. S. Pomrenke, R. L. Hengehold, and Y. K. Yeo, <u>Eur. J. Solid State Inorg. Chem.</u> t. 28, 1991, p 159.
- K. Takahei and A. Taguchi, 16th International Conference on Defects in Semiconductors, July 1991 (in print) and the literature therin.

The general review article which are not mentioned in the report and the references therein

- S. Larach, in <u>Proceedings of the International Conference on Luminescence</u>, <u>Budapest</u>, 1966, (Hungarian Academy of Sciences, Budapest, 1968), p 549 and references therein.
- M. R. Brown, A. F. J. Cox, W. A. Shand, and J. M. Williams, <u>Advances in Quantum</u> <u>Electronics Vol. 1</u>, ed. by D. W. Goodwin (Academic, New York, 1974), <u>Vol. 2</u>, 69.
- M. R. Brown, and W. A. Shand in <u>Advances in Quantum Electronics</u>, <u>Vol. 1</u>, ed. by D. W. Goodwin (Academic Press, New York, 1970), pp. 1-76.
- F. S. Bryant, Prog. Crystal Crowth and Charact., V. 6, 191 (1983).
- R. Boyn, phys. stat. sol. (b) 148, 11 (1988).
- G. S. Pomrenke, Ph. D. Dissertation, AFIT/DS/ENP/ 89-4, and references therin.
- K. R. Lee, M. S. M. Leask, and W. P. Wolf, J. Phys. Chem. Solids, 23, 1381 (1962).
- H. J. Lozykowski, <u>Proceedings of SPIE</u>, Vol. 836, 88 (1987).
- H. J. Lozykowski, Solid State Communications, Vol. 66, no.7, 755-759 (1988).
- H. J. Lozykowski, <u>Springer Proceedings in Physics</u>, <u>38</u>, Electroluminescence, Springer-Verlag, berlin, Heidelberg, 60 (1989).
- M. D. Galanin, Editor, Lumionescence Centers of Rare Earth Ions in Crystals Phosphors, <u>Proceedings of the Lebedev Physics Institute for the Academy of Science of the USSR</u>, <u>Vol. 175</u>, Nova Science Publishers, Commack, New York 11723.
- V. F. Masterov and L. F. Zakharenkov, <u>Sov. Phys. Semicond.</u>, 24 (4) 1990.