Effects of Temperature on Intra-Band Photoluminescence of Zinc Oxide (ZnO) Semiconductor

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Abstract In this paper, the Photoluminescence intensity of Zinc oxide compound semiconductor in conduction band to valence band, I_{CV}, conduction band to localized trap centre, I_{CT} and localized trap centre to valence band, I_{TV} radiative recombination mechanisms are discussed in different temperatures. By varying temperature, the dominated radiative recombination mechanisms are studied from the three radiative recombination mechanisms. At high values of temperature, the intensity of light in band-to-band radiative recombination mechanism dominates for all values of energies. For high values of impurity trap density, only the intensity of light in conduction band to trap level radiative recombination mechanisms dominates for all energies.

Keywords Radiative Recombination, Photoluminescence,Temperature,Zinc Oxide (ZnO),Localized State Energy.

1 Introduction

The beginning of semiconductor research is marked by Faraday's 1833 report on negative temperature coefficient of resistance of Silver sulfide . This is the first observation of any semiconductor property. In his 1833 paper, "Experimental Researches in Electricity" Faraday disclosed this observation. This observation was in distinction from the usual properties of metals and electrolytes in whose case resistance increases with temperature. The next significant contributor to semiconductor field is the French experimental physicist Edmond Becquerel. In 1839, he reported the observation of photovoltage in the silver chloride coated Platinum electrodes. In his experiment, a $AgCl$ coated Platinum electrode was immersed in an aqueous Nitric acid electrolyte solution. Illumination of the electrode generated photo-voltage that altered the electromagnetic field produced by the cell; in fact, it produced a reductive (cathodic) photocurrent at the $AgCl$ coated electrode. This was the first

reported photovoltaic device. Photovoltage was generated at the $Ag/AgCl$ metal semiconductor contact, Ag at the junction was formed by the absorbed silver clusters in the $AgCl$ electronic states [1].

Luminescence is one of the fastest growing and most useful analytical techniques in science and technology. The applications of luminescence can be found in various subject areas as materials science, microelectronics, clinical chemistry, biology, physics, environmental science, chemistry, toxicology, biochemistry, pharmaceuticals, and medicine. The term luminescence includes a wide variety of light-emitting processes, which originate their names from the varied sources of excitation energy that power them. Photoluminescence (PL) spectroscopy is a sensitive nondestructive technique, suitable for identifying point defects including extrinsic and intrinsic defects in materials [2]. It is a useful tool to evaluate the quality and to study the physical parameters of semiconductor materials in the form of thin films and nanomaterials. Zinc oxide (ZnO) is one of the promising semiconductor materials of II–VI group, because of its wider band gap (3.37 eV) and large excitation binding energy (60 meV) at room temperature [3]. ZnO thin films and nanostructures are increasingly being used in light-emitting diodes, solar cells, chemical sensors, photocatalysis, and antibacterial materials, etc., because of their unique physical properties [4].

In general, defects and impurities are playing an important role in the semiconductor industry to develop devices. In the case of ZnO material, it is very difficult to understand and study the role of defects or impurities in order to develop optoelectronic devices. Native or intrinsic defects are existing in the ZnO material such as oxygen vacancies (VO), zinc interstitials (Zni), oxygen interstitial (Oi), zinc vacancies (VZn), zinc antisites, and oxygen antisites. Understanding the incorporation and behavior of intrinsic defects in ZnO material is essential to its successful application in optoelectronic devices. These native defects have long been believed to play an important role in ZnO-based devices. The band-to-band excitation of ZnO

promotes electrons from the valence band to the conduction band, leaving holes in the valence band. The holes migrate from the valence band to deep levels and recombination occurs between electrons from either the conduction band or shallow donor levels and trapped holes on deep levels. Basically, the PL of ZnO is related to the presence of holes in the valence band [5]. The PL spectroscopy can help to understand the extrinsic and intrinsic defects in ZnO materials. Understanding of PL on ZnO nanostructure/thin films may lead to development of more efficient ZnO-based optoelectronic devices [6].

Zinc oxide is an inorganic compound with the chemical formula ZnO. It occurs as a white powder that is nearly insoluble in water. It crystallizes in two main forms, hexagonal wurtzite and cubic zinc blende structures. The wurtzite structure is more stable than the zinc blende structure. It is a wide-band gap semiconductor of the II-VI semiconductor group. Zinc oxide finds applications in the following: It is used for preventing corrosion in nuclear reactors, It is used as a pigment in paint, Coatings, Cigarette filters, Medicine etc. [7].

When electron-hole pairs are generated in a semiconductor, or when carriers are excited into higher impurity levels from which they fall to their equilibrium states, light can be given off by the material. Many of the semiconductors are well suited for light emission, particularly the compound semiconductors with direct band gaps. The general property of light emission is called luminescence. This overall category can be subdivided according to the excitation mechanism: If carriers are excited by photon absorption, the radiation resulting from the recombination of the excited carriers is called photoluminescence [8].

Photoluminescence involves the irradiation of the crystal to be characterized with photons of energy greater than the band-gap energy of that material. In the case of a crystal scintillator, the incident photons will create electron hole pairs. When these electrons and holes recombine, this recombination energy will transform partly into non-radiative emission and partly into radiative emission. Photoluminescence consists of impinging relatively high frequency light onto a material, exciting atomic electrons. Subsequent relaxation may result in the production of photons that are characteristic of the crystal or defect site that emits the light. The luminescent signals detected could result from the band-to-band recombination, intrinsic crystalline defects (growth defects), dopant impurities (introduced during growth or ion implantation), or other extrinsic defect levels (because of radiation or thermal effects). When bombarded with photons of energy greater than the band-gap of the material, an impurity energy level may emit characteristic photons via several different types of radiative recombination events, allowing the resultant PL spectra to be used to determine the specific type of semiconductor defect. This interaction provides a highly sensitive, qualitative measurement of native and extrinsic impurity levels found within the material band gap [9].

The basic difference between direct gap and indirect gap transitions is that, when the CBM and the VBM occur at the same value of wave number,k the material is said to be direct band-gap material. Conversely, when the CBM and the VBM occur at different values of , the material is said to be indirect band-gap material. Electronic transitions between the two bands, CBM and VBM in a direct material can take place with little or no change in crystal momentum. On the other hand, conservation of momentum during an inter-band transition is a major concern in indirect band-gap materials. There is a process, which involves the capture of electrons from the conduction band (or holes from the valence band) by the trap, followed by the recombination with holes in the valence band (or electrons in the conduction band). When electron-hole pairs (EHPs) recombine, energy is released through phonon emission and the localized state is called the recombination center. If the localized state captures free carriers temporarily and then re-emits them back to their original band, the center is called a free carrier trap. The localized trap states may be created by deep impurities, dislocations, radiation defects, grain boundaries, point defects and their complexes. The presence of defects in a semiconductor crystal due to impurities or crystallographic imperfections such as dislocations produces discrete energy levels within the band-gap. These defect levels, also known as traps, greatly facilitate recombination through a two-step process where a free electron from the conduction band first relaxes to the defect level and then relaxes to the valence band where it annihilates a hole [10].

In these work, upon the determination of the steady-state expressions for the occupation of free carriers at different energy levels, the relation between excess carrier concentrations is described. Then, by using illumination and net radiative recombination rate the luminescence intensity of light is determined for the corresponding radiative recombination mechanisms by assuming one photon ejects one electron at a time. Finally, by substituting the typical values for energy band gap, capture coefficients, acceptor energy levels and carrier's concentrations of the zinc oxide semiconductor, the photoluminescence intensity of radiative recombination mechanism at different temperature is determined for both localized state and transition energies.

2 Photoluminescence Intensity of Radiative Recombination Mechanisms

A large concentration of excess carriers can be maintained in a semiconductor under non-thermal equilibrium conditions and this alters the conduction properties of the specimen. The localized states are spatially distributed throughout the volume of the semiconductors. Therefore, n_T, p_T and the total density of the localized states N_T are given as a number per unit volume. The total density of the trap levels occupied by electrons, n_T and holes, p_T must equal to the total density of traps N_T [11].

$$N_T = n_T + p_T = n_{0T} + p_{0T} \qquad (1)$$

where, N_T is the total density of traps, n_T and p_T are the non-thermal equilibrium total density of the trap levels occupied by electrons and holes respectively. n_{0T} and p_{0T} are thermal equilibrium density of the trap levels occupied by electrons and holes respectively. Rearranging Eqn.(2) Yields:

$$\delta n_T = -\delta p_T \qquad (2)$$

Equation (2) shows that the trapping of electrons by the localized state removes the same amount of p_T states.

If there is illumination, the photo-generated electrons and holes are involved in the recombination processes. For the concentrations of photo-generated electrons (δn) and holes in the conduction band (δp), the respective changes of the concentrations of p_T and n_T states of a centre due to illumination, δn_T and δp_T are given by:

$$\delta n_T = n_T + p_{0T} \quad and \quad \delta p_T = p_T + n_{0T}, \qquad (3)$$

where, δn_T and δp_T are excess carriers concentrations of electrons and holes on the trap level respectively.

Suppose that δN density of electrons and δP densities of holes pairs generated in the conduction and valence bands, respectively in a semiconductor due to illumination; the total concentrations of excess electrons (δn) and holes (δp) under conduction in the respective conduction and valence bands are then given by:

$$\delta n = \delta N - \delta n_T, \quad and \quad \delta p = \delta P - \delta p_T \qquad (4)$$

For a system with only electron trap, $\delta p = \delta N = \delta P$, so that from (4) gives the photo-generated charge carrier neutrality equation for the system with an electron trap and hole's trap center to be:

$$\delta n + \delta n_T = \delta p, \quad \delta n = \delta p + \delta n_T \qquad (5)$$

The distribution probability f_n for the electron occupation of a trap located at energy E_T in the band gap is given by:

$$f_n = \frac{1}{1 + exp(\frac{E_T - E_F}{K_B T})} \qquad (6)$$

The thermal equilibrium electron occupancy n_{0T} and holes occupancy p_{0T} of the localized states are given by:

$$n_{0T} = f_n N_T, p_{0T} = N_T - n_{0T} \qquad (7)$$

The probability of electron capture by a localized state (U_{cn}) at thermal equilibrium is a function of the density of electrons in the conduction band (n_0), the electron capture coefficient of the state (C_{nT}), and the density of empty traps (p_{0T}). However, the probability of emission of an electron (U_{en}) depends only on the electron emission rate (e_n) and the density of traps occupied by electrons (n_{0T}). Thus, one can write U_{cn} and U_{en} as [12]

$$U_{cn} = C_{nT} n_0 p_{0T} \quad and \quad U_{en} = e_n n_{0T} \qquad (8)$$

The electron capture coefficient (C_{nT}) depends on the proximity of the Centre to the conduction band. Similarly, the probability of holes capture (U_{cp}), and the probability of holes emission (U_{ep}) are given by:

$$U_{cp} = C_{pT} p_0 n_{0T} \quad and \quad U_{ep} = e_p p_{0T} \qquad (9)$$

where e_p is the hole emission rate. The hole capture coefficient (C_{pT}) depends on the proximity of the center to the valance band.

According to the principle of detailed balance ($R_{th} = G_{th}$), the probability of capture and emission for each carrier is equal, so that we have:

$$U_{cn} = U_{en} \quad and \quad U_{cp} = U_{ep} \qquad (10)$$

Where, e_n and e_p are given by:

$$e_n = C_{nT} n_1 \quad and \quad e_p = C_{pT} p_1 \qquad (11)$$

where,

$$n_1 = n_i exp(\frac{E_T - E_i}{K_B T}) \, and \, p_1 = n_i exp(\frac{E_i - E_T}{K_B T}) \qquad (12)$$

are the concentrations of electrons and holes in the conduction and valence bands for the case in which the Fermi-level E_F falls at E_T. The fraction of photo-generated electrons, In trapped at the localized Centre to the excess electrons in the conduction band is given by:

$$I_n = \frac{\delta n_T}{\delta n} = \frac{\tau_{p0} p_{0T} - \tau_{n0} n_{0T}}{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta N) + \tau_{p0}(n_0 + n_1 + \delta N)} \qquad (13)$$

$$I_p = \frac{\delta p_T}{\delta p} = \frac{\tau_{n0} n_{0T} - \tau_{p0} p_{0T}}{\tau_{n0}(p_0 + p_1 + \delta P) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta P)} \qquad (14)$$

where δN is the total excess electron concentration generated in the conduction band and δP is the total excess hole concentration generated in the valence band. The subscripts n and p represent the electrons and holes concentration. τ_{n0} and τ_{p0} are time constants for a given center and is in general a function of the electron and hole capture coefficients of the center given by:

$$\tau_{n0} = \frac{1}{C_{nT} N_T} \quad and \quad \tau_{p0} = \frac{1}{C_{pT} N_T} \qquad (15)$$

Photoluminescence intensity of band-to-band radiative recombination mechanism, I_{CV}

The band-to-band radiative recombination is a direct recombination mechanism, in which the electrons in the conduction band decay to the valence band (i.e. recombine with holes in the valence band). This is a very efficient process in direct band gap semiconductors. The energy lost by an electron in making the transition is released as a photon. The total band-to-band radiative recombination rate R is directly proportional to the products of the concentration of electrons n available in the conduction band and the concentration of holes p available in the valence band to capture these electrons [13].

$$R = C_{CV} np \qquad (16)$$

where C_{CV} is a constant known as the coefficient of holes in the valence band for the capture of electrons from the conduction band. The capture probability C_{CV}, is described for direct band gap materials by van Roosbroeck and Shockley, using experimentally determined values of the optical absorption coefficient and the intrinsic carrier concentration as [14]

$$C_{CV} = e\pi \sqrt{k_\infty} (\frac{m_n}{m_n{}^* + m_p{}^*} \frac{300}{T})^{\frac{3}{2}} (1 + \frac{m_n}{m_n^*} + \frac{m_n}{m_p^*})[E_g^2] \qquad (17)$$

where e is the elemental charge and k_∞, the high frequency dielectric constant of the material. The respective net excess

photo-generate negative and positive charge carrier densities, δn and δp during illumination can be calculated by the difference between non-thermal equilibrium and thermal equilibrium charge carrier densities as:

$$\delta n = n - n_0 \quad and \quad \delta p = p - p_0 \tag{18}$$

The above recombination mechanism is written under non-thermal equilibrium circumstances. At thermal equilibrium, these recombination rates are given by:

$$R^{th} = C_{CV} n_0 p_0 \tag{19}$$

The net band-to-band radiative recombination rate, U_{CV} of free carriers is given by the difference between the band-to-band non-thermal equilibrium recombination mechanism, and the band-to-band thermal equilibrium recombination mechanisms:

$$U_{CV} = R - R^{th} = C_{CV}(p_0\delta n + n_0\delta p + \delta p\delta n) \tag{20}$$

Assuming a system with no free carrier trapping center (only band to band transition), the steady-state band to band free carrier's generation lifetime is given by:

$$\tau_g = \frac{\delta N}{U_{CV}} = \frac{\tau_{R0}\tau_k}{\tau_{R0} + \tau_k} \tag{21}$$

where τ_{R0} and τ_k are time constants related to low and high injection band to band free carriers generation rate given by [15]:

$$\tau_{R0} = \frac{1}{C_{CV}(n_0 + p_0)} \quad and \quad \tau_k = \frac{\tau_{R0}}{\sqrt{1 + 4C_R G_0 \tau_{R0}^2}} \tag{22}$$

where G_0 is optical generation rate of charge carriers. The ratio of the band to band recombination rate, U_{CV} to the free carrier generation rate, G_0 which is a direct measure of the band to band photoluminescence effect is given by:

$$I_{CV} = \frac{U_{CV}}{G_0} = \frac{C_{CV}(p_0\delta n + n_0\delta p + \delta n\delta p)}{G_0} \tag{23}$$

Photoluminescence intensity of conduction band to localized center radiative recombination mechanism, I_{CT}

The conduction band to localized center radiative recombination rate R_{CT} is directly proportional to the product of the concentration of electrons n available in the conduction band and the concentration of holes p_T states available in the localized state to capture electrons from the conduction band:

$$R_{CT} = C_{nT} n p_T \tag{24}$$

where C_{nT} is a constant known as the coefficient of holes in the localized state for the capture of electrons in conduction band is given by [16]

$$C_{CT} = 0.69 \times 10^{-12} \frac{\mu}{Z^2} \left(\frac{m_n}{m_n^*}\right)^{\frac{5}{2}} \left(\frac{300}{T}\right)^{\frac{1}{2}} [E_C - E_T] \tag{25}$$

The recombination mechanisms in (16) can be rewritten at thermal equilibrium as:

$$R_{CT}^{th} = C_{CT} n_0 p_{0T} \tag{26}$$

where, R_{CT}^{th} is thermal equilibrium conduction band to trap level radiative recombination rate.

The net conduction band to localized trap center radiative recombination rate of free carriers are given by:

$$U_{CT} = R_{CT} - R_{CT}^{th} = C_{CT}(p_{0T}\delta n + n_0\delta p_T + \delta p_T\delta n) \tag{27}$$

Or

$$U_{CT} = C_{CT}(p_{0T}\delta n + n_0 I_p\delta p + I_p\delta p\delta n) \tag{28}$$

The ration of the conduction band recombination rate of free carriers to the total optical generation rate of the free carriers, G_0 is given by:

$$I_{CT} = \frac{U_{CT}}{G_0} = \frac{C_{CT}(p_{0T}\delta n + n_0 I_p\delta p + I_p\delta p\delta n)}{G_0} \tag{29}$$

Photoluminescence intensity of localized state to valence band radiative recombination mechanism, I_{TV}

The localized state to valence band radiative recombination rate R_{TV} is :

$$R_{TV} = C_{TV} p n_T \tag{30}$$

where, C_{TV} is a constant known as the coefficient of holes in the valence band for the capture of electrons in the localized states and it is given by [17].

$$C_{TV} = 0.69 \times 10^{-12} \frac{\mu}{Z^2} (m_n/m_p^*)^{5/2} (300/T)^{1/2} (E_T - E_V) \tag{31}$$

The recombination mechanisms in (16) at thermal equilibrium, this recombination rate is given by:

$$R_{TV}^{th} = C_{TV} p_0 n_{0T} \tag{32}$$

The net localized trap center to valence band radiative recombination rate of free carriers are:

$$U_{TV} = R_V - R_V^{th} = C_{TV}(p_0\delta n_T + n_{0T}\delta p + \delta p\delta n_T) \tag{33}$$

Or

$$U_{TV} = C_{TV}(p_0 I_n\delta n + n_{0T}\delta p + I_n\delta p\delta n) \tag{34}$$

The intensity of light from the trap level to the valence band, I_{TV} is given by:

$$I_{TV} = \frac{U_{TV}}{G_0} = \frac{C_{TV}(n_{0T}\delta p + p_0 I_n\delta n + I_n\delta p\delta n)}{G_0} \tag{35}$$

The total concentration of excess electrons generated in the conduction band is given by:

$$\delta N = \frac{G_0\tau_g\tau_{CTg}}{\tau_g + \tau_{CTg}} \tag{36}$$

The total concentration of excess holes generated in the valence band is also given by:

$$\delta P = \frac{G_0\tau_g\tau_{TVg}}{\tau_g + \tau_{TVg}} \tag{37}$$

3 Numerical Result and Discussion

3.1 The competition between the Photoluminescence Intensity of different radiative recombination Mechanisms at different temperature

Temperature has its own effects on the luminescence intensity of radiative recombination mechanisms for zinc oxide compound semiconductor. The following figure is plotted for the three radiative recombination mechanisms under different temperature. It uses doping concentration of $N_a = 1.25 \times 10^{18} cm^{-3}$, illumination $G_0 = 1 \times 10^{25} cm^{-3}s^{-1}$, impurity density of trap $N_T = 1 \times 10^{17} cm^{-3}$ and $E_a = 0.01eV$ for different temperature.

Figure 1 (a) Illustrates that the intensity of light for band-to-band radiative recombination mechanisms at different temperature. The intensity of light in band-to-band radiative recombination decreases as temperature decreases. It decreases from 10^6 to 10^1 for a temperature range of $60K$ to $900K$. Increasing temperature in the conduction band to valence band increases number of electrons in the localized Centre. Due to the effects of trap, only small number of electrons recombine with holes in the valence band. These decreases the rate of recombination and hence, the intensity of light in the bands.

Figure 1 (b) Shows that the intensity of light for conduction band to trap level radiative recombination mechanisms at different temperature. The intensity of light in this band decreases with increasing temperature. At very low temperature it has high values of intensity of light and at high values of temperature $(T = 900K)$ it starts to increase from $0.5eV$ values of localized trap energy. As temperature increases the electrons in the conduction band increases and becomes ionized donors. The intensity of light is more effective at low temperature than high temperature. In the localized trap to valence band radiative recombination, the increasing of temperature increases the number of electrons in the localized Centre. Due to the effects of trap, the rate of recombination and intensity decreases as the temperature of the sample.

Figure 1(c) Shows that the intensity of light for trap level to valence band radiative recombination mechanisms at different temperature. The intensity of light decreases up to $0.5eV$ values of trap energy and remains constant up to $3eV$ and again start to decreases for the remaining energies.

3.2 The Photoluminescence Intensity of radiative recombination Mechanisms at different temperature in both localized energies and transition energies.

Figure 2 below, shows variation of photoluminescence intensities with localized energies at (a) 90 K, (b) 300 K and (c) 600 K in zinc oxide (ZnO)samples. It is plotted for the three radiative recombination mechanisms under different temperature. It uses doping concentration of $N_a = 1.25 \times 10^{17} cm^{-3}$, illumination $G_0 = 1 \times 10^{25} cm^{-3}s^{-1}$, impurity density of trap
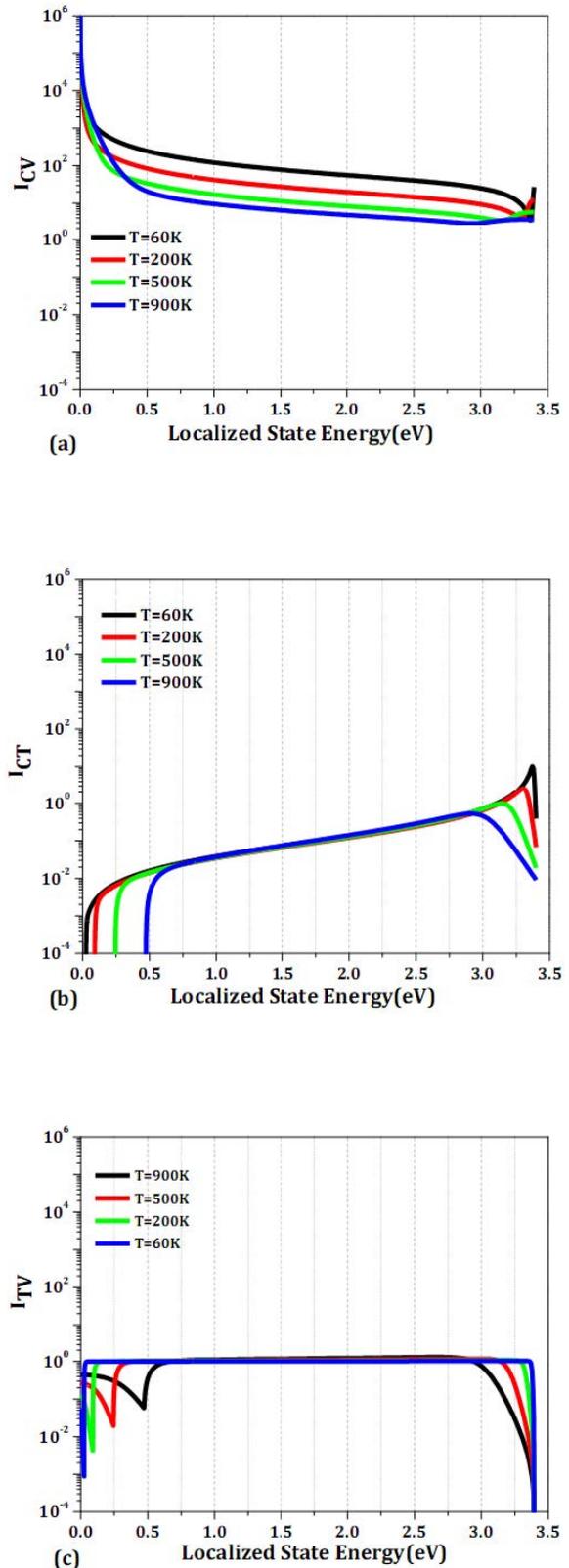

Figure 1: Luminescence Intensity at different temperature for zinc oxide (ZnO)samples in (a)conduction band to valence band, (b) conduction band to trap level and (c) trap level to valence band radiative recombination mechanisms.

$N_T = 1 \times 10^{17} cm^{-3}$ and $E_a = 0.01 eV$ for different temperature.

Figure 2 (a) Illustrates that the variation of photoluminescence intensities due to various electronic transition levels with localized energies at temperature of $60K$ and equal values of doping and impurity density. The intensity of light in band-to-band radiative recombination decreases from 10^4 to 10^{-1}. At high localized state energy, intensity becomes low. At high localized trap energy, there is excess of ionized donors in the conduction band. Band-to-band radiative recombination becomes dominant for all energies. The conduction band to localized trap level radiative recombination decreases from 10^0 to 10^2. At low localized state energy, intensity becomes high. At low localized state energy there is excess of ionized acceptors in the valence band and at high localized state energy there is excess of ionized donors in the conduction band. Both the intensity of conduction band to localized trap level and localized trap to valence band radiative recombination's are almost all the same at very low temperature and does not dominate for all energies.

Figure 2 (b) that the variation of photoluminescence intensities due to various electronic transition levels with localized energies at temperature of $300K$. The intensity of light in band-to-band radiative recombination decreases from 10^2 to 10^{-1}. At high localized trap energy, the intensity again increases due to the electrons in the conduction band becomes ionized donors. It dominates for low values of energy up to $2eV$. The intensity of light in the conduction band to localized trap level radiative recombination increases at very low energy due to hole trap effects. Then, it start to decreases from 10^0 to 10^1 and at high localized trap energy it start to increase because of electron s in the conduction bands becomes ionized donors. The localized trap level to valence band radiative recombination mechanism there is the effects of holes and electron trap. Due to these trap effect it's intensity decreases for low energies up to $0.2eV$ and start to increase from $0.2eV$ values of localized state energies. It dominates for energies between $2.25eV - 3.2eV$.

Figure 2(c) depicts the variation of photoluminescence intensities due to various electronic transition levels with localized energies at temperature of $900K$. The intensity of light in band-to-band radiative recombination dominates for low localized state energy up to $0.75eV$. The intensity of the conduction band to localized trap level radiative recombination dominates for the energy range from $0.75eV$ to $2.5eV$. The intensity of the localized trap level to valence band radiative recombination dominates for the energy starting from $2.5eV$.

Figure 3 Shows the variation of photoluminescence intensities with transition energies for the samples used in Figure 2. Figure 3(a) depicts that the variation of photoluminescence intensities at $T = 60K$. As shown in the figure, the luminescent band is conduction to valence band radiative recombination. Due to the effects of intra band transition, the intensity of the conduction band to localized trap level radiative recombination decreases from 10^{-2} to 10^0 and at high transition energy it becomes ionized donors. The intensity of the localized trap level to valence band radiative recombination decreases from 10^0 to 10^{-2} and at very low energy it becomes ionized acceptors.
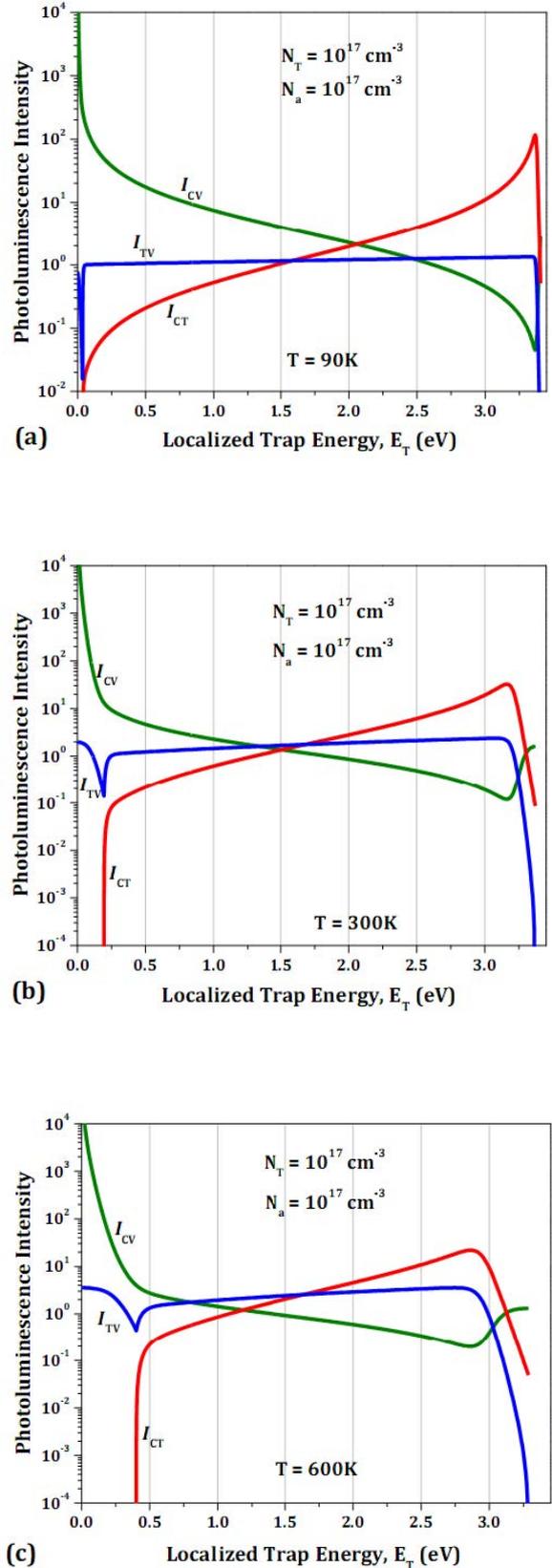

(a)

(b)

(c)

Figure 2: Variation of photoluminescence intensities with localized energies at (a) $60K$, (b) $300K$ and (c) $600K$ in zinc oxide (ZnO).

Figure 3(b) illustrates that the variation of photoluminescence intensities at $T = 300K$. The luminescent band is conduction to valence band radiative recombination. The intensity of the conduction band to localized trap level radiative recombination decreases at low transition energy due to hole capture effects. It starts to increase for the remaining energies and at high transition energy it becomes ionized donors. The intensity of the localized trap level to valence band radiative recombination decreases up to the recombination Centre for low energies and again start to decrease for higher energies due to electron trapping effects.
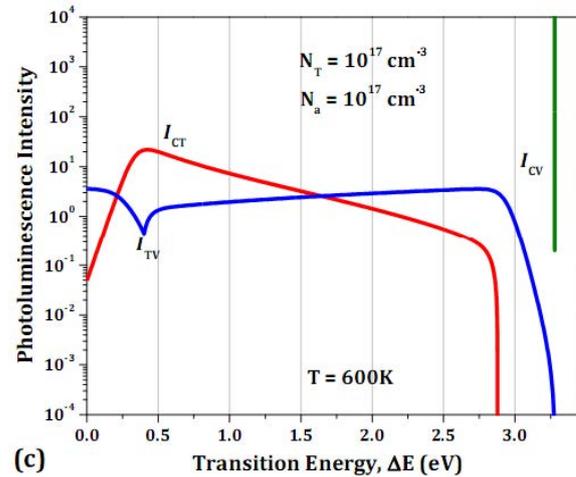
Figure 3(c) depicts that the variation of photoluminescence intensities at $T = 600K$. The luminescent band is again band to band radiative recombination. It's photoluminescence increases from 10^3 to 10^1 and shown at transition energy of $3.2 eV$.

(c)

(a)

(b)
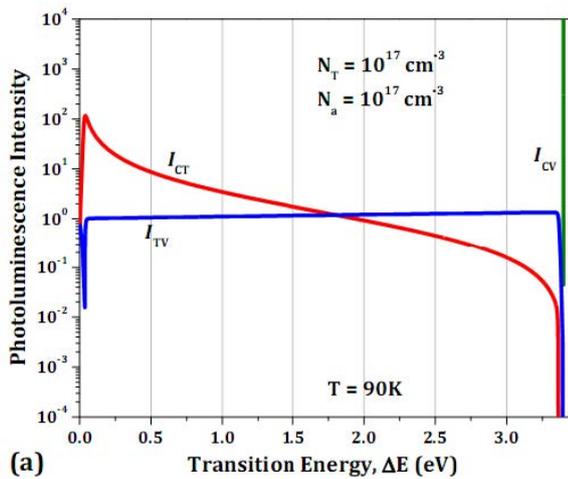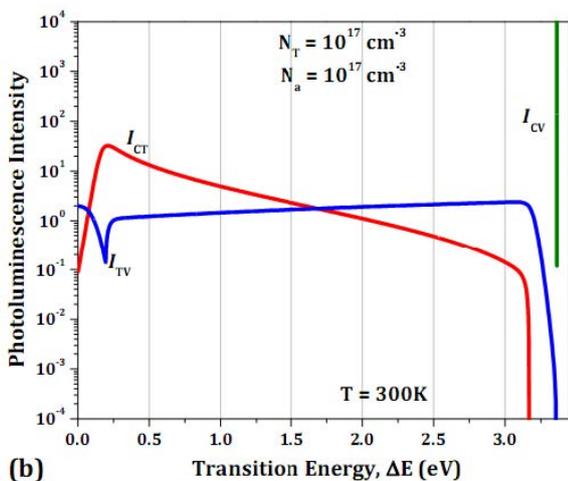
Figure 3: Variation of photoluminescence intensities with transition energies at (a) 90 K, (b) 300 K and (c) 600 K in zinc oxide (ZnO) sample.

4 Conclusion

In these work, we studied the effects of temperature on the photoluminescence of zinc oxide compound semiconductor. This effect is studied through different radiative recombination by varying temperature. The intensity of light depends on the amount of illumination and lifetime of excess electrons in the corresponding recombination mechanisms. It shows the amount of light in the bands and the more luminescent bands. Since there is no effects of traps in the conduction to valence band radiative recombination, rate of recombination is high and photoluminescence intensity becomes high. It was shown that due to trap effects in the conduction band to trap level radiative recombination, the recombination rate reduces and hence decreases the intensity of light in the band. Due to the effects of trap, only small amount of electrons on localized Centre and excess of holes in the valence band. These decreases the recombination rates and hence decreases the intensity of light in the Trap level to valence band radiative recombination.

Increasing temperature in the conduction band to localized state increases number of electrons in the localized Centre. At very low temperature, the electron trap becomes high and hole trap too small. Due to the effects of trap, only small number of electrons recombine with holes in the valence band. These decreases the rate of recombination and hence, the intensity of light in the bands. In the localized trap to valence band radiative recombination, the increasing of temperature increases the number of electrons in the localized Centre. Due to the effects of trap, the rate of recombination and intensity increases as the temperature of the sample increases.

Acknowledgements

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