

## Research Article

# EPR and Optical Absorption Spectral Investigations of $\text{Cu}^{2+}$ in $\text{Bi}_2\text{O}_3$ - $\text{ZnO}$ - $\text{B}_2\text{O}_3$ - $\text{Li}_2\text{O}$ Glasses

**Shashidhar Bale and Syed Rahman**

*Department of Physics, Osmania University, Hyderabad 500 007, India*

Correspondence should be addressed to Shashidhar Bale, sss\_bale@yahoo.co.in

Received 25 February 2012; Accepted 28 March 2012

Academic Editors: W. A. Badawy, J. Casado, and M. Mączka

Copyright © 2012 S. Bale and S. Rahman. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Electron paramagnetic resonance and optical absorption studies of  $\text{Bi}_2\text{O}_3$ - $\text{ZnO}$ - $\text{B}_2\text{O}_3$ - $\text{Li}_2\text{O}$  glasses were made by introducing  $\text{Cu}^{2+}$  as spin probe. The EPR spectra of  $\text{Cu}^{2+}$  in all the glass samples recorded in the X-band frequency have similar spectral features. The variation in glass composition influences the spin Hamiltonian parameters calculated from the spectra. The spin Hamiltonian parameters indicate that the  $\text{Cu}^{2+}$  ions are coordinated with six ligand atoms in a distorted octahedron elongated along one of the axes and the ground state of the  $\text{Cu}^{2+}$  is  $d_{x^2-y^2}$  orbital. The optical absorption spectra exhibited a broad band corresponding to d-d transition bands of  $\text{Cu}^{2+}$  ion. The values of bonding parameters indicate a covalent nature for the in-plane  $\sigma$  bonding and pure ionic nature for the in-plane and out-of-plane  $\pi$  bonding. The theoretical optical basicity parameter values were evaluated, and it was observed that the value of  $\Gamma_\sigma$  increases whereas  $\Gamma_\pi$  decreases with the increase in optical basicity.

## 1. Introduction

Electron paramagnetic resonance (EPR) studies of transition metal ions in oxide glasses is of scientific interest and gives information concerning the state of the ligands, the glass structure, nature of bonding, and site symmetry around metal ion [1–4]. The electron paramagnetic resonance (EPR) spectroscopic technique was first applied to glassy materials by Sands [1]. Unconventional glasses containing  $\text{Bi}_2\text{O}_3$  as glass former are of great interest because of their potential applications in industry and many allied areas [5–7]. EPR investigations of  $\text{Cu}^{2+}$  ions in glasses are interesting and have received a considerable attention due to the sensitivity of parameters to local symmetry and have been studied in wide variety of glasses [8–13]. Optical absorption of transition metal (TM) ions in glasses is influenced by host structure into which the transition metal ions are incorporated. In oxide glasses, the TM ions mostly form coordination complexes with doubly charged oxygen as the ligands. By correlating the EPR and optical absorption spectra, one can obtain information regarding the bond parameters that determine the metal-ligand bond in the glasses.

In this paper EPR and optical absorption properties of 1 mole % copper-doped  $(60-x)\text{Bi}_2\text{O}_3$ - $25\text{ZnO}$ - $15\text{B}_2\text{O}_3$ - $x\text{Li}_2\text{O}$

glasses ( $0 \leq x \leq 15$ ) are studied. The influence of  $\text{Li}_2\text{O}$  on the EPR and optical absorption parameters will be discussed. The variation of these parameters will be correlated with optical basicity of the glasses.

## 2. Experimental

In the present study copper-(1 mole %) doped glass samples of compositions  $(60-x)\text{Bi}_2\text{O}_3$ - $25\text{ZnO}$ - $15\text{B}_2\text{O}_3$ - $x\text{Li}_2\text{O}$  ( $0 \leq x \leq 15$ ) were prepared by melt quench technique using reagent grade chemicals  $\text{Bi}_2\text{O}_3$ ,  $\text{ZnO}$ ,  $\text{H}_3\text{BO}_3$ ,  $\text{Li}_2\text{CO}_3$ , and  $\text{CuO}$ . The mixture of these chemicals is taken in porcelain crucibles and was calcinated at  $450^\circ\text{C}$  for 1 h and then melted at  $1100$ – $1200^\circ\text{C}$  depending on the glass composition. The liquids were agitated for 1 h to ensure homogeneity in the mixture. The clear liquid was quickly cast in a stainless steel mould kept at  $200^\circ\text{C}$  and pressed with another steel disc to obtain glass. All samples were transparent and greenish in colour. The glasses were chemically stable and nonhygroscopic. Thus, the obtained glasses were annealed at  $200^\circ\text{C}$  for 12 h to remove thermal stress and strain.

The room temperature EPR spectra of powdered glass samples were recorded using a JEOL-1X-EPR spectrometer

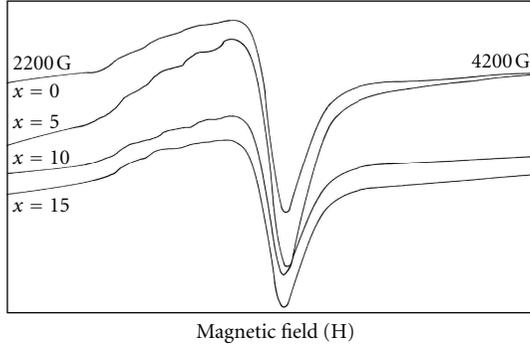


FIGURE 1: EPR spectra of  $\text{Cu}^{2+}$  in  $(60-x)\text{Bi}_2\text{O}_3\text{-}25\text{ZnO-}15\text{B}_2\text{O}_3\text{-}x\text{Li}_2\text{O}$  glasses.

in the range 2200 G–4200 G operating in the X-band and employing a field modulation of 100 kHz. DPPH was used as the standard  $g$  marker for the determination of magnetic field.

The optical absorption spectra of the present glass samples were recorded at room temperature using a double-beam Shimadzu spectrometer (model UV-3100) in the wavelength range 500–800 nm. The uncertainty in the observed wave length is about  $\pm 1$  nm.

### 3. Results and Discussion

**3.1. EPR Spectra.** The room temperature EPR spectra of the present glasses containing  $\text{Cu}^{2+}$  are shown in Figure 1. Each spectrum was analysed using the spin Hamiltonian:

$$\mathcal{H} = g_{\parallel}\beta H_z S_z + g_{\perp}\beta(H_x S_x + H_y S_y) + A_{\parallel}I_z S_z + A_{\perp}(I_x S_x + I_y S_y), \quad (1)$$

where the symbols have their usual meaning [14]. From the figure it is observed that the obtained absorption spectra are asymmetric, characteristic of  $\text{Cu}^{2+}$  ( $3d^9$ ) ions in axially distorted octahedral symmetric sites. It is found that the spectra keep their overall aspect in the entire composition range suggesting high structural stability of the glassy matrix to accept  $\text{Cu}^{2+}$  ions. The spectra show the hyperfine structure due to the interaction of the unpaired electron spin with the nuclear one,  $I = 3/2$ , characteristic of  $\text{Cu}^{2+}$ . The hyperfine structure is resolved in the parallel band of the spectra, and the perpendicular component is unresolved. Three hyperfine lines were observed on the parallel features of the spectrum. The variations in the hyperfine line widths can be attributed to the fluctuations in the coordination sphere surrounding the probe  $\text{Cu}^{2+}$  ion [15]. The values of spin Hamiltonian parameters  $g_{\parallel}$ ,  $g_{\perp}$ ,  $A_{\parallel}$ , and  $A_{\perp}$  were estimated from the spectra and are given in Table 1. The estimated values of  $g_{\parallel}$  and  $g_{\perp}$  satisfy the relationship  $g_{\parallel} > g_{\perp} > g_e (=2.0023)$  characteristic of  $\text{Cu}^{2+}$  ions coordinated with six ligand atoms in a distorted octahedron, elongated along one of the axes and the ground state of the  $\text{Cu}^{2+}$  is  $d_{x^2-y^2}$  orbital. This configuration satisfies the conditions for

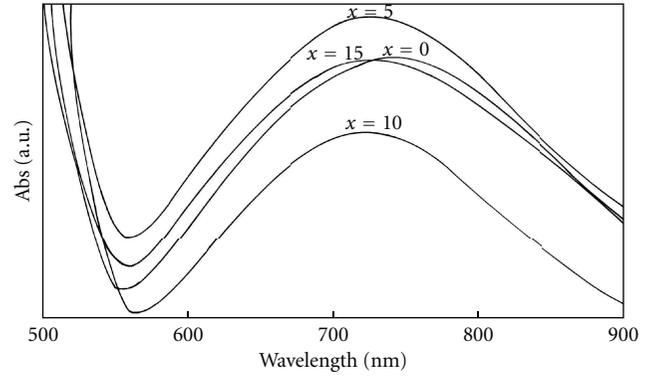


FIGURE 2: Optical absorption spectra of  $(60-x)\text{Bi}_2\text{O}_3\text{-}25\text{ZnO-}15\text{B}_2\text{O}_3\text{-}x\text{Li}_2\text{O}$  glasses.

applying the analysis developed by Maki and McGarvey [16] and modified by Kivelson and Neiman [17]. The change in spin Hamiltonian parameters with composition can be attributed to the variation of ligand field around the probe ion.

**3.2. Optical Absorption Spectra.** Figure 2 presents the optical absorption spectra of  $\text{Cu}^{2+}$  ions in the present glasses. A single absorption band in the near-infrared region was observed for all samples. This band in the near-infrared region can be identified as d-d transition band due to  $\text{Cu}^{2+}$  ions [18] and can be described in terms of ligand field theory [19]. In glasses it is assumed that due to vitreous state disorder, no site is perfectly cubic. Therefore, tetragonal distortions are endemic to the vitreous state, which leads to the splitting of energy levels. It is observed that the elongated structures are usually more energetically favoured than the compressed ones [20]. Hence, in the present investigation the observed asymmetric band is due to overlap of  ${}^2B_{1g} \rightarrow {}^2A_{1g}$  and  ${}^2B_{1g} \rightarrow {}^2B_{2g}$  transitions. Most of the authors [16, 17, 21, 22] assigned the observed optical peak to the  ${}^2B_{1g} \rightarrow {}^2B_{2g}$  transition ( $\Delta E_{xy}$ ) and have used this value in the evaluation of the bond parameters.

**3.3. Bond Parameters.** To determine the bonding coefficients of  $\text{Cu}^{2+}$ , one needs to know the absorption frequencies from the optical absorption bands. In a given glass,  $\Delta E_{xy}$  is the frequency of an intense absorption band of  $\text{Cu}^{2+}$  in the optical spectrum. By correlating EPR and optical absorption data, one can evaluate the bonding coefficients of  $\text{Cu}^{2+}$ . The bonding between the  $\text{Cu}^{2+}$  ion and its ligands can be described in terms of the covalency parameters  $\alpha^2$ ,  $\beta^2$ , and  $\beta_1^2$  where  $\alpha^2$  describes the in-plane  $\sigma$  bonding with the copper  $d_{x^2-y^2}$  orbital,  $\beta^2$  describes the out-of-plane  $\pi$  bonding with the  $d_{xz}$  and  $d_{yz}$  orbitals, and the  $\beta_1^2$  parameter is a measure of the in-plane  $\pi$  bonding with the  $d_{xy}$  orbital. The values of  $\alpha^2$  lie between 0.5 and 1, the limits of pure covalent and pure ionic bonding, respectively. The terms  $\beta^2$  and  $\beta_1^2$  can be interpreted similarly.

TABLE 1: EPR and optical parameters of the glass system (60-x)Bi<sub>2</sub>O<sub>3</sub>-25ZnO-15B<sub>2</sub>O<sub>3</sub>-xLi<sub>2</sub>O.

Parameters	x = 15	x = 10	x = 5	x = 0
$g_{  }$	2.337	2.332	2.333	2.312
$g_{\perp}$	2.127	2.127	2.079	2.056
$A_{  } \times 10^{-4}$ (cm <sup>-1</sup> )	160	114	108	99
$A_{\perp} \times 10^{-4}$ (cm <sup>-1</sup> )	49	60	48	55
$\lambda$ (nm)	717	712	719	727
$\Delta E_{xy}$ (cm <sup>-1</sup> )	13947	14044	13908	13755
$\alpha^2$	0.875	0.743	0.707	0.651
$\beta_1^2$	0.803	0.939	0.980	0.986
$\beta^2$	0.656	0.797	0.837	0.909
$\Gamma_{\sigma}$ (%)	27	56	63	76
$\Gamma_{\pi}$ (%)	39	12	3	2
$\Lambda_{th}$	0.954	0.963	0.973	0.982

The bonding parameters were evaluated using the equations given below [23]:

$$\alpha^2 = \left| \frac{A_{||}}{P} \right| + (g_{||} - 2) + \frac{3}{7}(g_{\perp} - 2) + 0.04,$$

$$\beta_1^2 = \left[ \left( \frac{g_{||}}{g_e} \right) - 1 \right] \frac{\Delta E_{xy}}{3312\alpha^2}, \quad (2)$$

$$\beta^2 = \left[ \left( \frac{g_{\perp}}{g_e} \right) - 1 \right] \frac{\Delta E_{xz,yz}}{828\alpha^2},$$

where  $P$  is the dipolar hyperfine coupling parameter,  $\Delta E_{xy}$  is the energy corresponding to the transition  ${}^2B_{1g} \rightarrow {}^2B_{2g}$ , and  $\lambda$  is the spin-orbit coupling constant ( $\lambda = -828$  cm<sup>-1</sup>).

The corresponding value of  $\Delta E_{xz,yz}$  was calculated using the approximation [24]

$$\Delta E_{xz,yz} = \frac{1656k^2}{(g_{\perp} - g_e)}, \quad (3)$$

where  $k^2$  is the orbital reduction factor (=0.77).

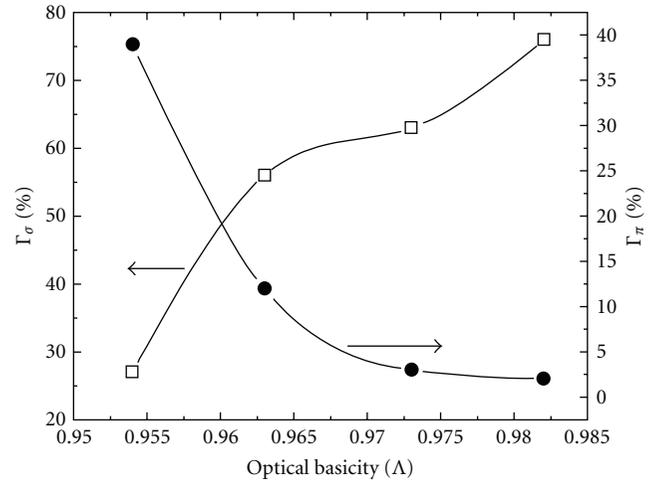
The normalized covalencies of Cu (II)-O in-plane bonds of  $\sigma$  and  $\pi$  symmetry are expressed in terms of bonding coefficients  $\alpha^2$  and  $\beta_1^2$  as follows [16]:

$$\Gamma_{\sigma} = \frac{200(1-S)(1-\alpha^2)}{(1-2S)}\%, \quad \Gamma_{\pi} = 200(1-\beta_1^2)\%, \quad (4)$$

where  $S$  is the overlap integral ( $S_{oxy} = 0.076$ ).

The calculated values of  $\alpha^2$ ,  $\beta_1^2$ ,  $\beta^2$ ,  $\Gamma_{\sigma}$ , and  $\Gamma_{\pi}$  are presented in Table 1. The normalized covalency of Cu(II)-O in-plane bonding of  $\pi$  symmetry ( $\Gamma_{\pi}$ ) indicates the basicity of the oxide ion. The values of  $\alpha^2$ ,  $\beta_1^2$ , and  $\beta^2$  indicate a covalent nature for the in-plane  $\sigma$  bonding and pure ionic nature for the in-plane and out-of-plane  $\pi$  bonding.

**3.4. Optical Basicity.** The optical basicity ( $\Lambda$ ) of an oxide medium as proposed by Duffy and Ingram [25] is a numerical expression of the average electron donor power of the oxide species constituting the medium. It is used as a measure of the acid-base properties of oxides, glasses, alloys, molten salts, and so forth. Theoretical optical basicity ( $\Lambda_{th}$ ), for the

FIGURE 3: Variation of  $\Gamma_{\sigma}$  and  $\Gamma_{\pi}$  with optical basicity ( $\Lambda$ ).

present glasses, can be calculated using the following equation, which is based on the approach proposed by Duffy [26]:

$$\Lambda_{th} = X_{Li_2O}\Lambda_{Li_2O} + X_{ZnO}\Lambda_{ZnO} + X_{Bi_2O_3}\Lambda_{Bi_2O_3} + X_{B_2O_3}\Lambda_{B_2O_3}, \quad (5)$$

where  $X_{Li_2O}$ ,  $X_{ZnO}$ ,  $X_{Bi_2O_3}$ , and  $X_{B_2O_3}$  are the contents of individual oxides in mole %.  $\Lambda_{Li_2O}$ ,  $\Lambda_{ZnO}$ ,  $\Lambda_{Bi_2O_3}$ , and  $\Lambda_{B_2O_3}$  are the theoretical optical basicity values assigned to oxides present in the glass. The values  $\Lambda_{Li_2O} = 1$ ,  $\Lambda_{ZnO} = 8.2$ ,  $\Lambda_{Bi_2O_3} = 1.19$ , and  $\Lambda_{B_2O_3} = 0.42$  are used in the present study [26, 27]. The  $\Lambda_{th}$  values calculated using the above equation for the present glasses are given in Table 1. It can be seen from Table 1 that the theoretical optical basicity increases slightly with increasing  $Bi_2O_3$  content, which can be attributed to the high polarizability of bismuth ions. Similar observations were reported earlier [6, 28]. The variation of  $\Gamma_{\sigma}$  and  $\Gamma_{\pi}$  with optical basicity is represented in Figure 3. It is observed that there is an overall increase in  $\Gamma_{\sigma}$  whereas  $\Gamma_{\pi}$  decreases with the increase in optical basicity. The optical basicity can also be used to classify the covalent/ionic ratios of the glasses since an increase in the optical basicity indicates decreasing

covalency. Therefore, in the present investigation, with the increase in  $\text{Bi}_2\text{O}_3$  content, optical basicity increases and hence the covalency between  $\text{Cu}^{2+}$  ions and oxygen ligands decreases, which is clear from  $\Gamma_\pi$  values. Similar observation was reported by [11, 29].

#### 4. Conclusions

From the values  $g_{\parallel} > g_{\perp} > g_e$  (2.0023), it is concluded that the ground state of  $\text{Cu}^{2+}$  ions in all the samples under study in the present paper is  $d_{x^2-y^2}$  orbital ( ${}^2B_{1g}$  state) and the site symmetry around  $\text{Cu}^{2+}$  ion is tetragonally distorted octahedral sites.

From the nature and position of the absorption band observed, it can be inferred that the band corresponds to  ${}^2B_{1g} \rightarrow {}^2B_{2g}$  transition.

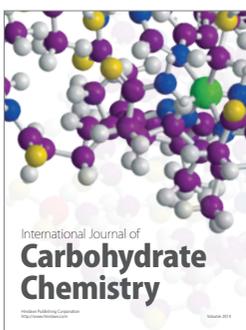
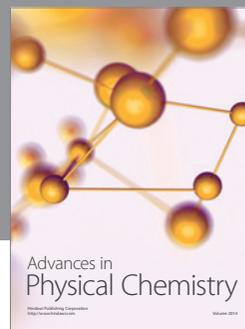
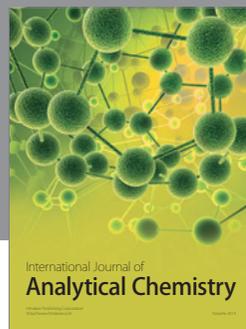
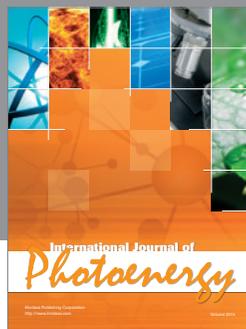
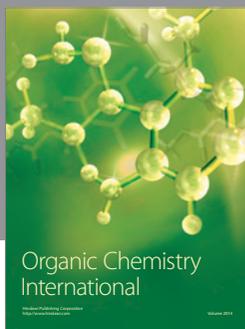
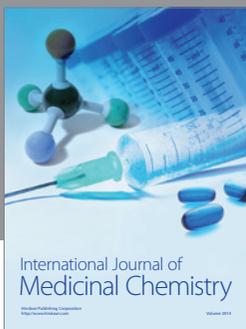
The values of the bonding parameters indicate that the in-plane sigma bonding is covalent whereas the in-plane and out-of-plane  $\pi$  bonding is ionic in nature. The change in the spin Hamiltonian parameters with  $\text{Li}_2\text{O}$  content is attributed to the change in local structure.

The value of  $\Gamma_\sigma$  increases whereas  $\Gamma_\pi$  decreases with the increase in optical basicity and hence the covalency between  $\text{Cu}^{2+}$  ions and oxygen ligands decreases.

#### References

- [1] R. H. Sands, "Synchrotron oscillations induced by radiation fluctuations," *Physical Review*, vol. 97, no. 2, pp. 470–473, 1955.
- [2] H. Imagava, "Polariton dispersion in biaxial and uniaxial crystals," *Physica Status Solidi*, vol. 30, no. 2, pp. 449–454, 1968.
- [3] L. D. Bogomolowa, "The effects of copper impurity in vanadate and tungsten-phosphate glasses," *Journal of Non-Crystalline Solids*, vol. 30, no. 3, pp. 379–383, 1979.
- [4] D. L. Griscom and R. E. Griscom, "Paramagnetic resonance of  $\text{Mn}^{2+}$  in glasses and compounds of the lithium borate system," *Journal of Chemical Physics*, vol. 47, no. 8, pp. 2711–2722, 1967.
- [5] C. Stehle, C. Vira, D. Vira, D. Hogan, S. Feller, and M. Affatigato, "Optical and physical properties of bismuth borate glasses related to structure," *Physics and Chemistry of Glasses*, vol. 39, no. 2, pp. 83–86, 1998.
- [6] S. Bale, N. S. Rao, and S. Rahman, "Spectroscopic studies of  $\text{Bi}_2\text{O}_3\text{-Li}_2\text{O-ZnO-B}_2\text{O}_3$  glasses," *Solid State Sciences*, vol. 10, no. 3, pp. 326–331, 2008.
- [7] S. Bale, M. Purnima, C. H. Srinivasu, and S. Rahman, "Vibrational spectra and structure of bismuth based quaternary glasses," *Journal of Alloys and Compounds*, vol. 457, no. 1-2, pp. 545–548, 2008.
- [8] N. Srinivasa Rao, S. Bale, M. Purnima, K. Siva Kumar, and S. Rahman, "Optical absorption and electron spin resonance studies of  $\text{Cu}^{2+}$  in  $\text{Li}_2\text{O-Na}_2\text{O-B}_2\text{O}_3\text{-As}_2\text{O}_3$  glasses," *Bulletin of Materials Science*, vol. 28, no. 6, pp. 589–592, 2005.
- [9] B. Sumalatha, I. Omkaram, T. R. Rao, and Ch. L. Raju, "Alkaline earth zinc borate glasses doped with  $\text{Cu}^{2+}$  ions studied by EPR, optical and IR techniques," *Journal of Non-Crystalline Solids*, vol. 357, no. 16-17, pp. 3143–3152, 2011.
- [10] I. Ardelean, M. Peteanu, R. Ciceo-Lucacel, and I. Bratu, "Structural investigation of  $\text{CuO}$  containing strontium-borate glasses by means of EPR and IR spectrometry," *Journal of Materials Science*, vol. 11, no. 1, pp. 11–16, 2000.
- [11] G. Ramadevudu, M. Shareefuddin, N. Sunitha Bai, M. L. Rao, and M. N. Chary, "Electron paramagnetic resonance and optical absorption studies of  $\text{Cu}^{2+}$  spin probe in  $\text{MgO-Na}_2\text{O-B}_2\text{O}_3$  ternary glasses," *Journal of Non-Crystalline Solids*, vol. 278, no. 1–3, pp. 205–212, 2000.
- [12] S. Bale and S. Rahman, "Optical absorption and EPR studies on  $(70-x)\text{Bi}_2\text{O}_3\text{-Li}_2\text{O-30}(\text{ZnO-B}_2\text{O}_3)$  ( $0 \leq x \leq 20$ ) glasses," *Journal of Non-Crystalline Solids*, vol. 355, no. 43-44, pp. 2127–2133, 2009.
- [13] O. Cozar, D. A. Magdas, and I. Ardelean, "EPR study of molybdenum-lead-phosphate glasses," *Journal of Non-Crystalline Solids*, vol. 354, no. 10-11, pp. 1032–1035, 2008.
- [14] B. Bleaney, K. D. Bowers, and D. J. E. Ingram, "Paramagnetic resonance in diluted copper salts. I. Hyperfine structure in diluted copper tutton salts," *Proceedings of the Royal Society A*, vol. 228, no. 1173, pp. 147–157, 1955.
- [15] H. Kawazoe, H. Hosono, and T. Kanazawa, "Electronic structure and properties of oxide glasses (I)  $\pi$ -electron distribution on alkali borate glass networks," *Journal of Non-Crystalline Solids*, vol. 29, no. 2, pp. 159–171, 1978.
- [16] A. H. Maki and B. R. McGarvey, "Electron spin resonance in transition metal chelates. I. Copper (II) bis-acetylacetonate," *The Journal of Chemical Physics*, vol. 29, no. 1, article 31, 4 pages, 1958.
- [17] D. Kivelson and R. Neiman, "ESR studies on the bonding in copper complexes," *The Journal of Chemical Physics*, vol. 35, no. 2, 7 pages, 1961.
- [18] I. Siegel and J. A. Lorenc, "Paramagnetic resonance of copper in amorphous and polycrystalline  $\text{GeO}_2$ ," *The Journal of Chemical Physics*, vol. 45, no. 6, article 2315, 6 pages, 1966.
- [19] T. Bates, *Modern Aspects of the Vitreous State*, vol. 2, Butterworths, London, UK, 1962.
- [20] C. K. Jorgensen, "Comparative crystal field studies of some ligands and the lowest singlet state of paramagnetic nickel(II) complexes," *Acta Chemica Scandinavica*, vol. 9, pp. 1362–1377, 1955.
- [21] A. H. Dietzel, "On the so-called mixed alkali effect," *Physics and Chemistry of Glasses*, vol. 24, no. 6, pp. 172–180, 1983.
- [22] B. V. Raghavaiah, C. Laxmikanth, and N. Veeraiyah, "Spectroscopic studies of titanium ions in  $\text{PbO-Sb}_2\text{O}_3\text{-As}_2\text{O}_3$  glass system," *Optics Communications*, vol. 235, no. 4–6, pp. 341–349, 2004.
- [23] G. van Veen, "Simulation and analysis of EPR spectra of paramagnetic ions in powders," *Journal of Magnetic Resonance*, vol. 30, no. 1, pp. 91–109, 1978.
- [24] H. G. Hetch and T. S. Johnston, "Study of the structure of vanadium in soda-boric oxide glasses," *The Journal of Chemical Physics*, vol. 46, no. 1, article 23, 12 pages, 1967.
- [25] J. A. Duffy and M. D. Ingram, "Establishment of an optical scale for lewis basicity in inorganic oxyacids, molten salts, and glasses," *Journal of the American Chemical Society*, vol. 93, no. 24, pp. 6448–6454, 1971.
- [26] J. A. Duffy, "Electronic polarisability and related properties of the oxide ion," *Physics and Chemistry of Glasses*, vol. 30, no. 1, pp. 1–4, 1989.
- [27] R. W. Young, J. A. Duffy, G. J. Hassall, and Z. Xu, "Use of optical basicity concept for determining phosphorus and sulfur slag-metal partitions," *Ironmaking and Steelmaking*, vol. 19, no. 3, pp. 201–219, 1992.

- [28] S. Sindhu, S. Sanghi, A. Agarwal, V. P. Seth, and N. Kishore, "Effect of  $\text{Bi}_2\text{O}_3$  content on the optical band gap, density and electrical conductivity of  $\text{MO}\cdot\text{Bi}_2\text{O}_3\cdot\text{B}_2\text{O}_3$  ( $\text{M} = \text{Ba}, \text{Sr}$ ) glasses," *Materials Chemistry and Physics*, vol. 90, no. 1, pp. 83–89, 2005.
- [29] R. P. Sreekanth Chakradhar, B. Yasoda, J. L. Rao, and N. O. Gopal, "Mixed alkali effect in  $\text{Li}_2\text{O}\text{--}\text{Na}_2\text{O}\text{--}\text{B}_2\text{O}_3$  glasses containing  $\text{Fe}_2\text{O}_3$ —an EPR and optical absorption study," *Materials Research Bulletin*, vol. 41, no. 9, pp. 1646–1656, 2006.



**Hindawi**

Submit your manuscripts at  
<http://www.hindawi.com>

