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TECHNICAL REPORT NO. 21

PREPARATION AND CHARACTERIZATION OF SEVERAL
CONDUCTION TRANSITION METAL OXIDES

BY

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PREPARED FOR SYMPOSIUM M
MATERIALS RESEARCH SOCIETY
SAN DIEGO, APRIL 1989

May 24, 1989

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION unclassified		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED	
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S) #21		5. MONITORING ORGANIZATION REPORT NUMBER(S) NOO0 14 86 0234 DAVID NELSON	
6a. NAME OF PERFORMING ORGANIZATION BROWN UNIVERSITY AARON WOLD	6b. OFFICE SYMBOL <i>(if applicable)</i>	7a. NAME OF MONITORING ORGANIZATION OFFICE OF NAVAL RESEARCH	
6c. ADDRESS (City, State, and ZIP Code) DEPARTMENT OF CHEMISTRY PROVIDENCE, RI 02912		7b. ADDRESS (City, State, and ZIP Code) CODE 472 800 N. QUINCY STREET ARLINGTON, VA 22217	
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL <i>(if applicable)</i>	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO.	PROJECT NO.
		TASK NO.	WORK UNIT NO.
11. TITLE (Include Security Classification) PREPARATION AND CHARACTERIZATION OF SEVERAL CONDUCTION TRANSITION METAL OXIDES			
12. PERSONAL AUTHOR(S) AARON WOLD AND KIRBY DWIGHT			
13a. TYPE OF REPORT TECHNICAL	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Year, Month, Day) MAY 24, 1989	15. PAGE COUNT 11
16. SUPPLEMENTARY NOTATION TO BE PUBLISHED WITH MRS SYMPOSIUM M, APRIL 1989 PROCEEDINGS.			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
19. ABSTRACT (Continue on reverse if necessary and identify by block number) The structure-property relationships of several conducting transition metal oxides, as well as their preparative methods, are presented in this paper. The importance of preparing homogenous phases with precisely known stoichiometry is emphasized. A comparison is also made of the various techniques used to prepare both polycrystalline and single crystal samples. For transition metal oxides, the metallic properties are discussed either in terms of metal-metal distances which are short enough to result in metallic behavior, or in terms of the formation of a μ^* conduction band resulting from covalent metal-oxygen interactions. Metallic behavior is observed when the conduction bands are populated with either electrons or holes. The concentration of these carriers can be affected by either cation or anion substitutions. The discussion in this presentation will be limited to the elements Re, Ti, V, Cr, Mo and Cu. <i>CTY</i>			
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS PPT <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL		22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

PREPARATION AND CHARACTERIZATION
OF SEVERAL CONDUCTING TRANSITION METAL OXIDES

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ABSTRACT

The structure-property relationships of several conducting transition metal oxides, as well as their preparative methods, are presented in this paper. The importance of preparing homogeneous phases with precisely known stoichiometry is emphasized. A comparison is also made of the various techniques used to prepare both polycrystalline and single crystal samples. For transition metal oxides, the metallic properties are discussed either in terms of metal-metal distances which are short enough to result in metallic behavior, or in terms of the formation of a π^* conduction band resulting from covalent metal-oxygen interactions. Metallic behavior is observed when the conduction bands are populated with either electrons or holes. The concentration of these carriers can be affected by either cation or anion substitutions. The discussion in this presentation will be limited to the elements Re, Ti, V, Cr, Mo, and Cu.

INTRODUCTION

It is not possible in this paper to discuss all of the known conducting oxides. This treatment will be limited to a number of binary and complex oxides which have been carefully prepared and characterized. It is hoped that the review of these representative conducting transition metal oxides will enable the reader to appreciate the importance of careful chemistry in the understanding of their properties. The structure and electronic properties of transition metal oxides depend on the stoichiometry and homogeneity of the prepared phases. Poorly prepared compounds cannot be effectively characterized. Consequently, an understanding of the variables which influence homogeneity and stoichiometry is important if progress is to be made in developing new oxides which are both of fundamental interest and useful for practical applications. In this paper the discussion will be limited to three structure types, namely ReO_3 , rutile and CuO . The discussion of each structure type will be illustrated with specific compounds and will encompass problems encountered in their preparation and characterization. The relationship between structure, stoichiometry and conductivity will be emphasized, and correlations will be made in terms of the one-electron energy diagrams proposed and used so successfully by J. B. Goodenough.

Rhenium(VI) Oxide

Biltz and his co-workers first reported the preparation of ReO_3 [1,2]. Improved methods for its preparation were described by Nechankin et al. [3]. The oxide is red and reported to be diamagnetic [4]. Ferretti, Rogers and Goodenough [5] indicated that ReO_3 exists with a considerable range of composition. Since the electrical properties are dependent on the sample stoichiometry, pure stoichiometric single crystals were grown by chemical vapor transport of ReO_3 obtained by the reduction of Re_2O_7 with CO . Non-stoichiometric ReO_3 was produced by the reduction process, but purified when transported in a two-zone furnace with iodine as the transport agent. The transported, purified crystals were found to be stoichiometric within the limits of the analytical procedure used ($\pm 0.2\%$) [6]. Resistivity measurements made on single crystals of stoichiometric ReO_3 [5] indicated that they exhibited metallic behavior.

In the ReO_3 structure (Fig. 1), the oxygen atoms occupy three-quarters of the positions in a cubic close-packed type lattice. The rhenium atoms occupy one-quarter of the available octahedral sites. The unit of structure, as represented in Fig. 1, is a simple cube of rhenium atoms with oxygen atoms on all of the twelve edge centers. The cubic ReO_3 structure is the simplest three-dimensional structure formed from vertex sharing of octahedral (ReO_6) groups. Each rhenium, therefore, has six oxygen nearest neighbors and each oxygen atom has two rhenium neighbors arranged linearly.

According to Morin [7] and Goodenough [8], for ReO_3 where rhenium is in the +6 oxidation state, the crystal environment permits the formation of a conduction band by π overlapping of the metal "d" orbitals with the p_π orbital of the oxygen. For the ReO_3 structure (Fig. 2), each anion contributes two σ orbitals (sp) and two π orbitals p_π^2 . Each octahedrally coordinated cation contributes six σ orbitals ($e_g^2sp^3$) and three π orbitals (t^3_{2g}). A large overlap of the metal t^3_{2g} and anion p_π orbitals can result in the formation of bonding and antibonding π bands (Fig. 2) [8]. In Fig. 2, the σ and π bands are composed of bonding orbitals and the σ^* and π^* bands of antibonding orbitals. The p_π^* energy level is a non-bonding state and is composed of anion p_π orbitals. The number of states is designated by $[n]$ and refers to the spin and orbital degeneracies per molecule. ReO_3 has 25 outer electrons per molecule and hence can fill up to one-sixth of the total number of π^* states. Hence, this model is consistent with the observed metallic behavior of ReO_3 .

This model was confirmed by Ferretti, Rogers and Goodenough [5] who compared the electrical conductivity of single crystals of ReO_3 with that of sintered bars of polycrystalline $\text{Sr}_2\text{MgReO}_6$. The latter compound is an ordered perovskite and was first prepared by Longo and Ward [9]. In this compound, the rhenium and magnesium atoms are at the centers of oxygen octahedra which are linked by vertex sharing. $\text{Sr}_2\text{MgReO}_6$ differs from ReO_3 in that Mg^{2+} and Re^{6+} are in a nearly perfect ordered arrangement; the rhenium atoms cannot approach each other through oxygen more closely than about 7.6Å. However, in ReO_3 , the Re atoms are about 3.8Å apart.

Ferretti et al. [5] carried out an investigation to distinguish between models for the conduction band involving either direct overlap of t_{2g} orbitals across the face diagonal of the unit cell or indirect overlap (π bonding) of the t_{2g} metal orbitals and the oxygen p_π orbital. The former model would allow both compounds to be metallic, but the latter predicts metallic behavior (delocalized d-electrons) for ReO_3 and semiconducting behavior, at most, for $\text{Sr}_2\text{MgReO}_6$. $\text{Sr}_2\text{MgReO}_6$ was found to be a semiconductor which is consistent with metal-oxygen-metal overlap. Rhenium trioxide single crystals were found to be metallic conductors with conductivities approaching that of metallic silver. The compound was found to be diamagnetic, indicating that the weak Pauli paramagnetic moment expected from the conduction electrons is insufficient to overcome the diamagnetism of the electrons in closed shells.

TiO_2 and Transition Metal Dioxides with the Rutile Structure

One of the polymorphs of TiO_2 , rutile, crystallizes with the structure shown in Fig. 3 (space group $P4_2/mnm$). The metal coordinates are: $\text{Ti}(0,0,0)$, $(1/2,1/2,1/2)$ and $0;\pm(x,x,0)$, $\pm(1/2+x,1/2-x,1/2)$. As can be seen from Fig. 3, the structure consists of chains of TiO_6 octahedra and each pair share opposite edges. Each titanium atom is surrounded octahedrally by six oxygen atoms, whereas each oxygen is surrounded by three titanium atoms arranged as corners of an equilateral triangle. The structure, therefore, has a 6:3 coordination.

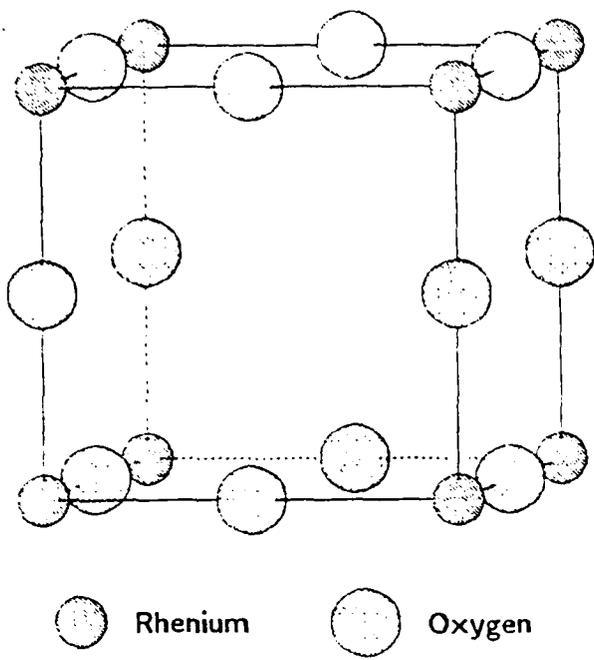


Fig. 1. Structure of ReO_3

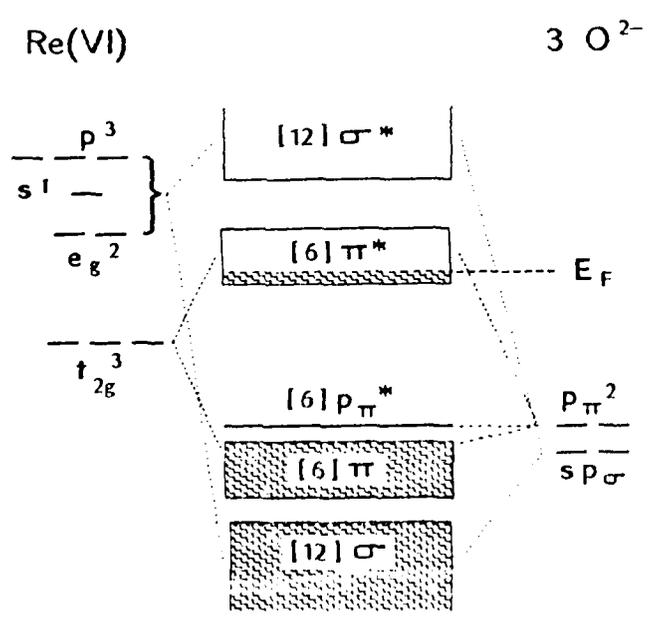


Fig. 2. Schematic Energy Bands for ReO_3



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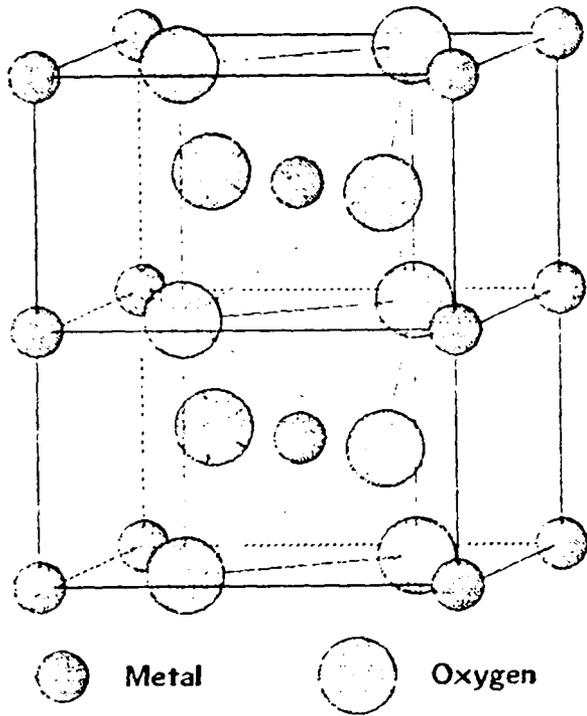


Fig. 3. Rutile Structure

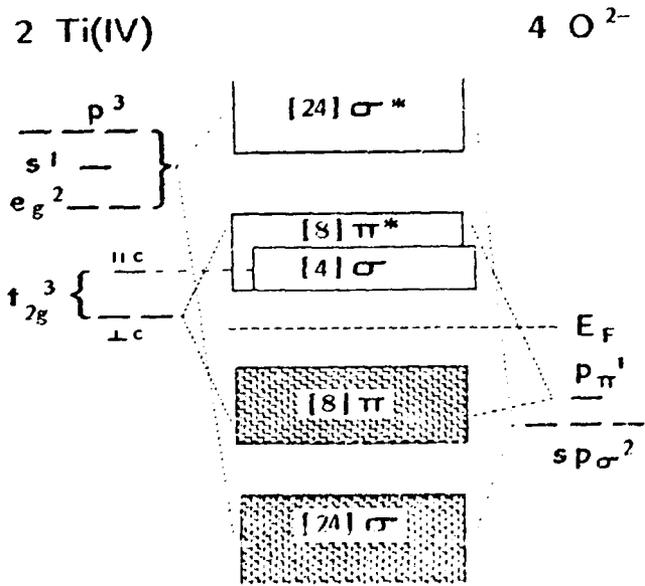


Fig. 4. Schematic Energy Bands for TiO_2

A number of transition metal dioxides crystallize with rutile-related structures. Magnéli et al. [10-13], as well as Goodenough [8,14], have related certain properties of various transition metal dioxides to the number of transition metal d-electrons. Goodenough [8] has proposed, and Rogers [15] has applied, a one-electron energy diagram for TiO_2 (rutile) and related compounds (Fig. 4). In this diagram the metal $e_g^2sp^3$ wave functions of a doubled formula unit Ti_2O_4 are mixed with hybridized sp^2 wave functions of oxygen to form bonding and antibonding σ states. As a result of the long range ordering of the structure, the states are broadened to form bands with finite widths. Interaction between two t_{2g} cation orbitals ($t_{2g\perp c}$) with the remaining oxygen p_{π} gives rise to bonding and antibonding π bands. The $t_{2g\parallel c}$ orbitals of the cations are directed along the c axis and may form a σ band if the metal-metal separation is small enough for significant overlap to occur. The allowable number of electrons that can be accommodated by any band is given in brackets, and this number is equal to the product of the number of atoms per formula unit, the orbital degeneracy per atom and the spin degeneracy per atom. The rutile TiO_2 has an electronic configuration of $3d^0$ for Ti(IV). The Ti-O σ and π bands are completely filled so that the Fermi level is located at the middle of the energy gap between these bands and the antibonding π^* and cation-cation d-bands. Hence, TiO_2 (rutile) should be a semiconductor and become metallic when the Fermi level is raised as the TiO_2 is reduced to form some Ti(III) $3d^1$ states.

Vanadium (IV) Oxides

The vanadium oxides with compositions between V_2O_3 and VO_2 are formed from slabs of a rutile-like structure sharing faces. Each of these phases shows transitions from the semiconducting to metallic state. Many of their properties can also be explained by considering structural changes which occur at the transition and utilizing the concepts of Goodenough [8] in which strong covalent mixing with oxygen p_{π} orbitals to form a π^* band plays a central role (Fig. 5a). For VO_2 , above the transition temperature of 67°C , these bands overlap and are partially filled, giving rise to metallic conductivity. The compound is tetragonal ($P4_2/mnm$) and all the V-V distances are equal (2.87Å). Below the transition temperature, the formation of V-V pairs along the tetragonal c-axis causes a doubling of the crystallographic unit cell [16], and a splitting of the $t_{2g\parallel c}$ orbital in two (Fig. 5b). The resulting lower σ level lies below the bottom of the π^* band, becomes filled and lowers the Fermi energy below the bottom of the π^* band. The π^* band, arising from covalent mixing, is now empty [8]. Excitation of electrons from the filled σ level to the bottom of the π^* band gives rise to the semiconducting behavior.

Other Transition Metal Dioxides Crystallizing with the Rutile Structure

The simple model proposed by Goodenough [8,14] has been applied by Rogers [15] to account for the electronic behavior of the transition metal dioxides with rutile-like structures. Molybdenum(IV) oxide has 2 unpaired electrons for each molybdenum atom. Therefore, one electron is available for Mo-Mo σ bonding and the second electron can partially fill the Mo-O π^* band (Fig.6). However, the short Mo-Mo separation is not fully consistent with a single σ bond. Hence, some of the electrons from the metal oxygen π band are promoted to a metal-metal π band which is located at the same energy level as the metal-metal σ state [15].

For CrO_2 , Rogers [15] has indicated that there is a sharp decrease in direct cation-cation bonding. Hence, the $t_{2g\parallel c}$ do not enter into metal-metal σ bonds, but remain at discrete cation sites $\parallel c$ in this compound (Fig. 7). The existence of these non-bonding sites within the π^* band is consistent with the

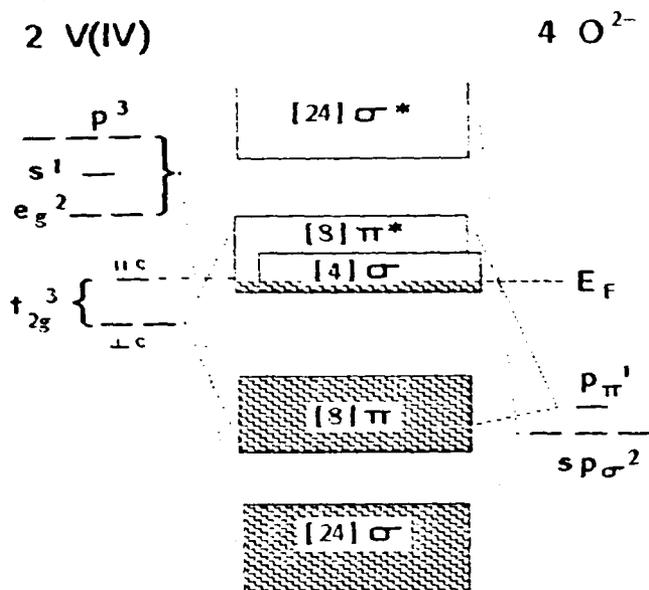


Fig. 5a. Schematic Energy Bands for Tetragonal VO_2

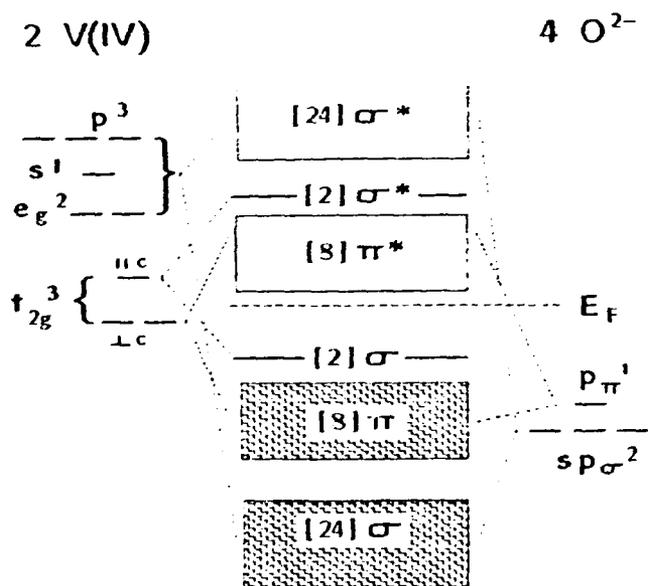


Fig. 5b. Schematic Energy Bands for Monoclinic VO_2

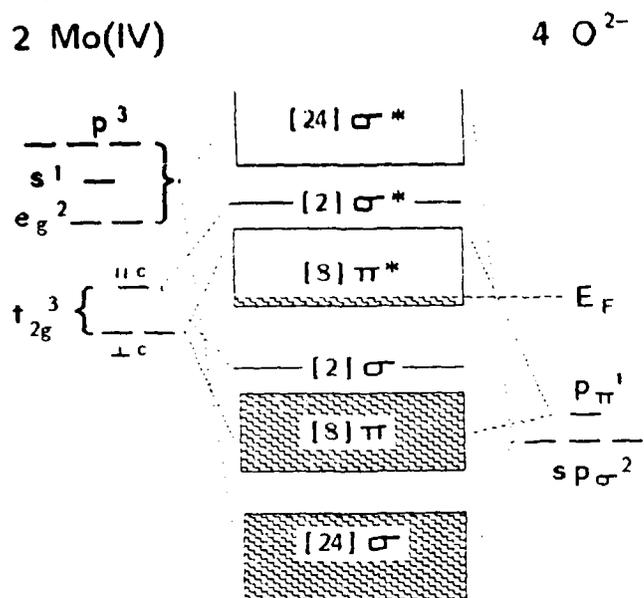


Fig. 6. Schematic Energy Bands for MoO₃

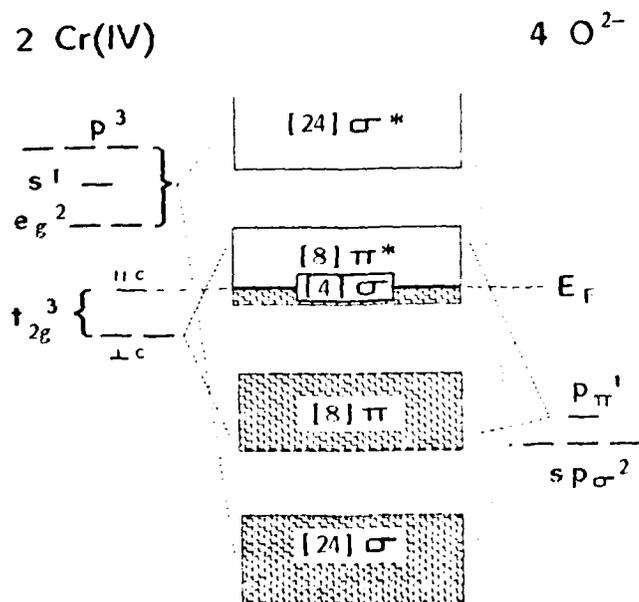


Fig. 7. Schematic Energy Bands for CrO₂

observed ferromagnetic metallic properties of CrO_3 . A number of the platinum metal dioxides, e.g. Ru, Ir, Os and possibly Rh, show metallic behavior which is consistent with the partial filling of the metal-oxygen π^* band. For PtO_2 where the π^* band is filled, the Fermi level is raised to lie between the π^* and σ^* bands and the compound should behave as a semiconductor. Rogers [15] has reported powder samples of PtO_2 to be semiconducting.

Copper Oxides

Copper(II) oxide occurs in nature as the mineral tenorite. The structure [17] shows Cu(II) with square planar coordination of oxygen around the copper. The space group is $C2/c$ with unit cell dimensions $a = 4.6837(5)\text{\AA}$, $b = 3.4226(5)\text{\AA}$, $c = 5.1288(6)\text{\AA}$ and $\beta = 99.54(1)^\circ$. Fig. 8 shows the chains of oxygen coordination parallelograms formed by sharing edges. The structure is a distorted PdO type with two O-Cu-O angles of 84.5° and two of 95.5° . Each copper has 4 O' neighbors at 1.96\AA and two next nearest O'' neighbors at 2.78\AA . The line O''-Cu-O'' is inclined at 17° to the normal to the $\text{Cu(O}')_4$ plane and the shortest Cu-Cu distance is 2.90\AA .

Another oxide of copper, $\text{Cu}_{16}\text{O}_{14}$ has been reported [18]. It is the rare mineral paramelaconite and crystallizes with the space group $I4_1/amd$, with unit cell dimensions $a = 5.817\text{\AA}$, $c = 9.803\text{\AA}$. The structure is related to tenorite but the oxygen vacancies result in a rearrangement of the monoclinic tenorite structure to a tetragonal one.

In Cu(II) oxide, the Jahn-Teller distortion due to the stabilization of a single d-hole per atom, $\text{Cu(II)}3d^9$, results in the observed difference of its structure with the monoxides of the other first row transition metals. For CuO, the equatorial oxygen p_σ overlaps strongly with the $d_{(x^2-y^2)}$ orbital to form σ bands, but little, if any, with the $d_{(z^2)}$. The copper d_{xy} , d_{yz} , d_{xz} orbitals contribute to the formation of π bands. O'Keefe and Stone [19], Roden et al. [20], as well as Yang et al. [21], have indicated that CuO is antiferromagnetic with an observed anomaly in the magnetic susceptibility at 230 K. The Goodenough band model [22,23] indicates that when antiferromagnetic behavior is observed in the copper oxides, a separation may occur between the empty σ^* band states of the Cu(II/I) couple and the occupied σ^* band states of the Cu(III/II) couple. This is shown in Fig. 9 where the Fermi energy is placed near the top of the filled π^* band. The antiferromagnetic behavior of CuO is not typical, since the data reported by Roden [20] do not show a maximum of χ at the antiferromagnetic ordering temperature. The unusual ordering can be related to the magnitude, or even existence, of the σ^* bandsplitting. In the case where Cu(III) is formed, the sign of the carrier results unambiguously from the formation of holes in the top of the π^* band. Where Cu(I) is formed, in addition to any electrons entering the σ^* (Cu(II/I) band, holes in the π^* band are also created by thermal excitation. Since the σ^* bands are narrow, the greater mobility of the holes in the π^* band will determine the sign of the dominant carrier. Koffeyberg [24] has indicated that CuO can only be prepared as p-type.

ACKNOWLEDGEMENTS

This research was partially supported by GTE Labs, Inc., Waltham, Massachusetts, by the Office of Naval Research, and by the National Science Foundation, Grant No. DMR-8901270.

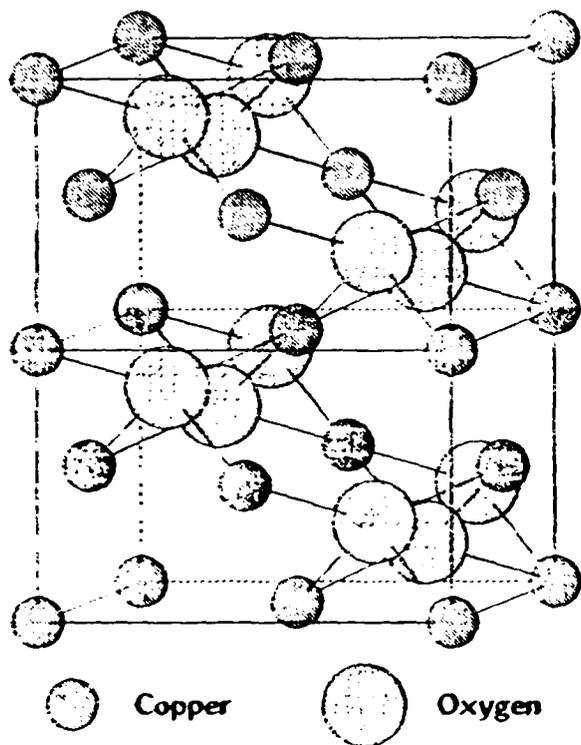


Fig. 8. Structure of CuO

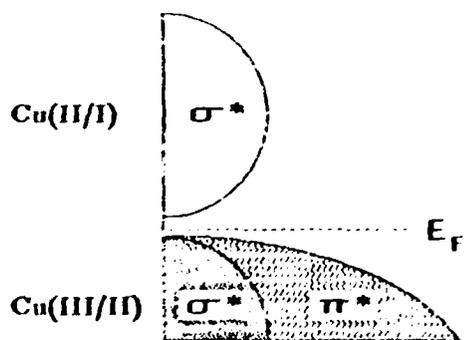


Fig. 9. Schematic Band Structure for CuO

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