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DATA COMPILATION ON VANADIUM OXIDES

M. NEUBERGER

NOVEMBER 1971

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UNCLASSIFIED
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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Hughes Aircraft Company
Culver City, California 90230

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
Data Compilation on Vanadium Oxides

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Interim Report

5. AUTHOR(S) *(First name, middle initial, last name)*
M. Neuberger

6. REPORT DATE
November 1971

7a. TOTAL NO. OF PAGES
61

7b. NO. OF REFS
116

8a. CONTRACT OR GRANT NO.
DSA 900-72-C-1182

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
EPIC-IR-79

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES
Copies are available from NTIS for $6.00 each.

12. SPONSORING MILITARY ACTIVITY
U.S. Defense Supply Agency
Defense Electronics Supply Center
Dayton, Ohio

13. ABSTRACT

The change in crystal structure at the transition temperature in several of the vanadium oxides, causes a drastic change in resistivity as the material is heated (or cooled). This phenomenon is being applied to the manufacture of a number of devices.

All available information on the crystal structure, physical, mechanical, thermal, optical, magnetic and electronic properties of bulk and film samples, has been tabulated in this compilation. Graphs illustrating these features are included.

DD FORM 1 NOV 65 1473

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14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Vanadium Oxides						
Transition Metal Oxides						
Electrical Properties						
Optical Properties						
Magnetic Properties						
Thermal Properties						
Mechanical Properties						
Crystallographic Properties						
Phase Diagrams						
Electronic Switching Devices						

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EPIC-IR-79

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ACKNOWLEDGEMENT

The Electronic Properties Information Center is operated by Hughes Aircraft Company under contract to the U.S. Defense Supply Agency (DSA 900-72-C-1182); technical aspects of EPIC operations are monitored by the Air Force Materials Laboratory. The support of these sponsor organizations is gratefully acknowledged.

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Library of Congress Catalog Card Number: 75-1857[illegible]8

ABSTRACT

The change in crystal structure at the transition temperature in several of the vanadium oxides, causes a drastic change in resistivity as the material is heated (or cooled). This phenomenon is being applied to the manufacture of a number of devices.

All available information on the crystal structure, physical, mechanical, thermal, optical, magnetic and electronic properties of bulk and film samples, has been tabulated in this compilation. Graphs illustrating these features are included.

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INTRODUCTION

Several vanadium oxides, $VO_{0.8-1.3}$, V_2O_3 and an entire series of non-stoichiometric vanadium oxides, show a crystallographic transformation from a low to high temperature phase. According to Hyland,* there is no extensive rearrangement of the atoms, only slight distortions of the original atomic grouping which is rapidly reversible at the transition temperature. Fillingham in an optical study of the domain structure in VO_2, indicates that displacement of the atom positions is small and comprises only slight distortions of the VO_6-octahedra chains as vanadium atom doublets form, alternately nearer to and farther from one another in the low temperature (monoclinic) phase. As the crystal moves through the transition temperature, domain patterns show only in the monoclinic phase, there are no domains evident in the tetragonal phase.

These alternating long and short separations of the cations along the a-axis (2.65Å and 3.12Å) shift above the transition temperature and the cations form a body-centered tetragonal array; V-V = 2.87Å along the c-axis. As a result, $a_{monoclinic} = 2c_{tetragonal}$ and Z-2 becomes Z-4.

This shift in crystal structure must evidently exercise a strong effect on the electronic properties of the several vanadium oxides and, consequently, on the band structure. The most marked and useful change is a rise in conductivity as the vanadium dioxide is heated through its transition temperature of 68°C where the material passes from a semiconducting to a metallic state. The conductivity is 5 orders of magnitude in VO_2 and 9 orders of magnitude in V_2O_3. The shift is also anisotropic and, depending on the sample quality, may also exhibit hysteresis.

Single crystals in the series V_nO_{2n-x} with x equal to an integer, have been studied by Okinaka et al., Kosuge and Nagasawa. Transition temperatures in this series vary from 68°C to -140°C. The composition V_5O_9 has a resistivity jump on cooling through 125°K of $\sim 10^7$ Ωcm and together with V_6O_{11} shows an increase in thermal emf at the transition temperature from -10 to -800 μV/°K.

* All references are listed alphabetically by name, in the bibliography at the end of this report.

This change in the several properties of the vanadium oxides is being applied to the manufacture of a variety of switching and modulation devices, since the time constant is about 20 nanoseconds. (Schmidt, Cope & Penn, Walden, Kennedy & Collins, Van Steensel).

Other electronic and physical properties also show a discontinuity at the transition temperature; magnetic susceptibility, thermoelectric power, specific heat, thermal expansion, reflectivity and transmission spectra. Graphs illustrating these features are included.

Band structures have been formulated, based in general on the theoretical considerations of Goodenough, by many experimentalists. These include Hyland, Verleur et al., Bongers, Powell et al., Berglund & Guggenheim, Austin & Turner, Mokerov & Rakov and Adler. Austin & Mott, in a recent discussion of the transition metal oxides, ascribe their properties to Coulomb interactions between the d-electrons and a strong electron-lattice coupling. With others in this field, they also agree that disorder and defects have a marked influence in leading to localized electron states. There is, apparently, a general agreement that the transition phenomena are primarily lattice dominated, but a band structure which will satisfy both electrical and optical considerations has not yet been formulated.

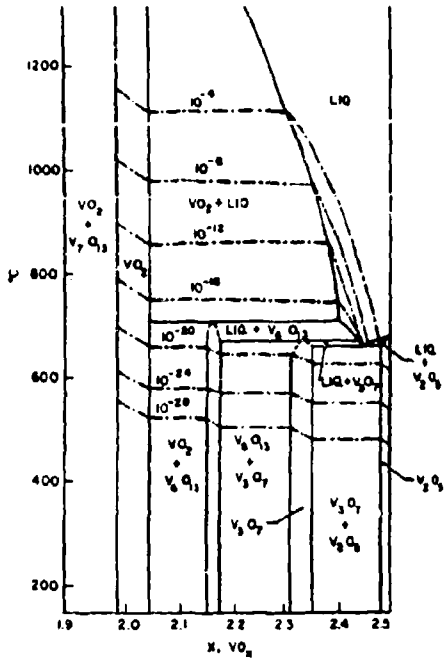
In general, electrical and magnetic data yield a one-electron band model with relatively large electron-phonon interactions. In a band structure derived from optical data, Verleur et al. propose a model for VO_2 above the transition temperature, in which filled valence bands (associated with the oxygen) are separated from partially filled conduction bands (arising from the vanadium), with the lowest vanadium bands slightly overlapping one or more of the partially filled bands. On this basis, the VO_2 at temperatures above the transition, would be a semi-metal, rather than a metal. In the model derived from optical data, VO_2 at temperatures below the transition would have electrons trapped in localized levels or occupying two completely filled bands. In any event, much more experimental data on crystals of high purity and stoichiometric quality are needed to choose a realistic band structure model.

Repeated cycling of crystals of VO_2 causes cracking and to obviate this difficulty, Hensler, Fuls, Rozgony and their associates have prepared sputtered, polycrystalline films, 500 to 4000 Å thick, annealed at 400°C. These randomly oriented thin films, when carried through the heating and cooling cycle, show new random configurations with the same properties as previously and may, therefore be considered stable.

Vanadium monoxide is stable over a composition range of $VO_{0.8}$ to $VO_{1.3}$. Density measurements indicate that stoichiometric samples are highly defective and analysis of infrared spectra by Ariya & Golomolzina led them to the conclusion that the monoxide comprises regions of vanadium alternating with regions of V_2O_3.

The data tables which follow, cover all vanadium oxides known to date, including those which do not show any phase transition. Pertinent curves for the several properties covered in the tables are inserted, following each stoichiometric compound. A few graphs have been included for chromium, aluminum or titanium doped vanadium oxides for their value in device applications, but these materials will be more fully covered in a later report.

PHASE DIAGRAM



Vanadium-Oxygen phase diagram, on the basis of recent data.

------ oxygen partial pressure (atm)

—·—·— estimated oxygen pressure

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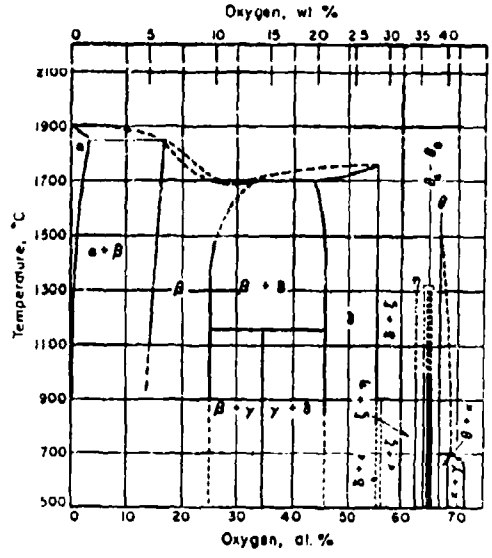
MacChesney & Guggenheim,
Kosuge, B
MacChesney et al.



Vanadium-Oxygen System

Stringer

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Phase Analyses of vanadium oxides by magnetic susceptibility measurements and x-ray diffraction measurements.

Kosuge, B

VO_x	Phase	VO_x	Phase	VO_x	Phase
1·50	V_2O_3	1·84	$V_6O_{11}+V_7O_{13}$	2·30	$V_6O_{13}+V_3O_7$
1·51	V_2O_3	1·85	$V_6O_{11}+V_7O_{13}$	2·32	V_2O_7
1·52	$V_2O_3+V_3O_5$	1·86	V_7O_{13}	2·34	V_3O_7
1·64	$V_3O_5+V_2O_3$	1·87	$V_7O_{13}+VO_2$	2·36	$V_3O_7+V_2O_5$
1·65	V_3O_5	1·97	$VO_2+V_7O_{13}$	2·38	$V_3O_7+V_2O_5$
1·66	V_3O_5	1·98	$VO_2+V_7O_{13}$	2·40	$V_3O_7+V_2O_5$
1·67	V_3O_5	1·99	VO_2	2·42	$V_3O_7+V_2O_5$
1·68	$V_3O_5+V_4O_7$	2·00	VO_2	2·45	$V_2O_5+V_3O_7$
1·73	$V_4O_7+V_3O_5$	2·01	VO_2	2·47	$V_2O_5+V_3O_7$
1·74	V_4O_7	2·02	VO_2	2·48	V_2O_5
1·75	V_4O_7	2·03	$VO_2+V_6O_{13}$	2·50	V_2O_5
1·76	$V_4O_7+V_5O_9$	2·10	$VO_2+V_6O_{13}$		
1·77	$V_5O_9+V_4O_7$	2·15	$V_6O_{13}+VO_2$		
1·78	$V_6O_7+V_4O_7$	2·16	V_6O_{13}		
1·79	$V_5O_9+V_4O_7$	2·166	V_6O_{13}		
1·80	V_5O_9	2·17	V_6O_{13}		
1·81	$V_5O_9+V_6O_{11}$	2·18	$V_6O_{13}+V_3O_7$		
1·82	$V_6O_{11}+V_5O_9$	2·20	$V_6O_{13}+V_3O_7$		
1·83	V_6O_{11}	2·25	$V_6O_{13}+V_3O_7$		

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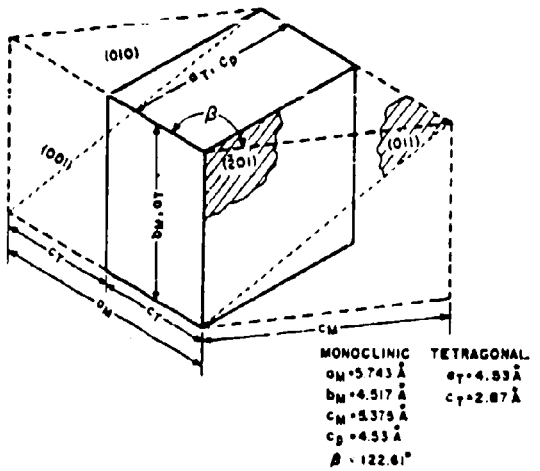
CRYSTAL STRUCTURE



VO_2

Relation between tetragonal unit (high temperature, solid lines) and monoclinic unit (low temperature, dashed lines).

Major monoclinic planes are shown.

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Simplified structure of V_2O_3 showing only the vanadium ion position.

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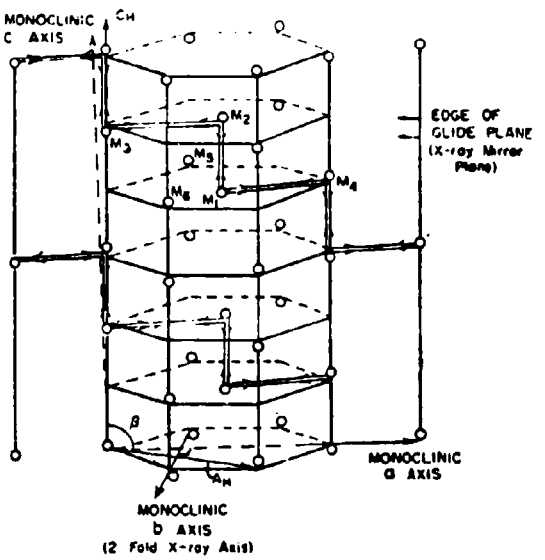


THE VANADIUM-OXYGEN SYSTEM

PHYSICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		VO				
Stability range		$VO_{0.8}$-$VO_{1.3}$		(Possible: VO= $V+V_2O_3$)		Stringer, Adler
Molecular Wgt.		66.95				
Density		5.92	g/cm^3	6.49 (calc.)		Donnay
Color		light grey				Handbook
Symmetry		cubic				Donnay
Space Group		Fm3m Z-4				Donnay
Lattice Parameters	a_o	4.099	Å			Massard et al.
		4.093				Donnay
	V-V	2.93				Bongers

VO_x	a_o (Å)	Density (g/cc)	Vacancies (%)		
0.86	4.034	5.736	37.0	sintered at 1300°C	Banus et al.
0.96	4.058	5.674	31.7		
0.99	4.068	5.602	30.8		
1.02	4.077	5.583	28.9		
1.23	4.133	5.329	21.2		
1.30	4.14	5.85	22	single crystal, zero oxygen vacancies	

Melting Point		1720	°C	in vacuo		Stringer
Specific Heat		0.014	cal/g °K		50	TPRC, p. 528
		0.158			300	
		0.225			1700	

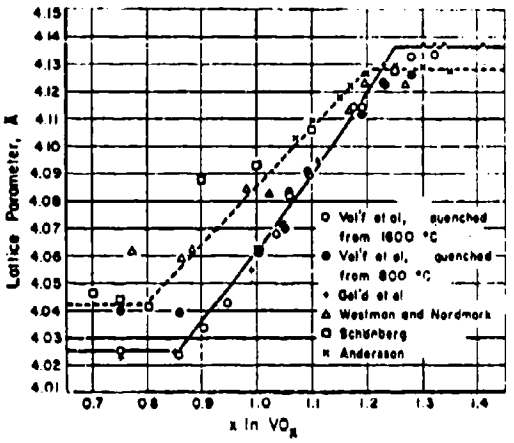
THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Resistivity	$VO_{.83-.86}$	$VO_{1.02}$	$VO_{1.2}$			
	8×10^{-4}	6×10^{-3}	Ω-cm	sintered	4	Honig et al.
	8×10^{-4}	5×10^{-3}	9×10^{-1}	sintered, shows no T_c	77	Banus et al.
	8×10^{-4}	2×10^{-3}	10^{-2}		300	
	$VO_{.919}$	$VO_{1.147}$	$VO_{1.25}$			
	2×10^{-3}	3×10^{-2}	— Ω-cm	sintered to 90% density, shows no T_c	100	Kawano et al. [A]
	10^{-3}	2×10^{-2}	2×10^{-1}		115	
	8×10^{-4}	5×10^{-3}	6×10^{-3}		300	
		2×10^{-3}	Ω-cm	1-5μ, epitaxial film on MgO, no T_c	77-300	Takei & Koide [A]
		0.4×10^{-3}		0.3μ film, $VO_{0.2}$	300	Hensler et al.
		0.8×10^{-3}		0.1μ film, $VO_{1.2}$		
Temp. Coeff.		-3×10^{-5}	$°C^{-1}$	0.3μ film, $VO_{0.2}$		Hensler et al.
		-10^{-3}		0.1μ film, $VO_{1.2}$		
Resistivity		10^{7}	Ω-cm	$VO_{0.9}$	94	Austin
		10^{6}		VO, single crystal	83	Morin
		10^{-2}			300	
Transition Temp. T_c		114 126	°K	cooling heating		Morin
Pressure Coeff.	dT_c/dP	-3	10^{3} °K/bar	P= 25 kbars	94, 113	Austin
Transition Temp.		88-125	°K	NMR meas., range due to variations in stoichiometry		Warren et al.

THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Energy Gap		6	meV	high V content		Banus et al., Kawano et al.[A]
		0.157	eV	low V content		
Seebeck Coeff.	$VO_{.88}$ $VO_{.99}$ $VO_{1.05}$ $VO_{1.23}$					
	-12 -4 +5 +22		μV/°K	sintered	300	Banus et al.
	$VO_{.85}$ VO $VO_{1.05}$ $VO_{1.26}$					
	-5 +3 +8 +26			sintered to 90% density	300	Kawano et al.[B]
	0 +3 +17					
Magnetic Susceptibility	X_g	6	10^{-6} cgs	sintered, VO	300	Massard et al.
		8		sintered	90	Bogdanova & Loginov
		5			300	
	$VO_{.92}$ $VO_{1.07}$ $VO_{1.26}$					
	25 80 115		10^{-6} cgs	sintered	2-7	Kawano et al.[A]

$VO_{0.7-1.4}$



Lattice Parameters as a function of composition.

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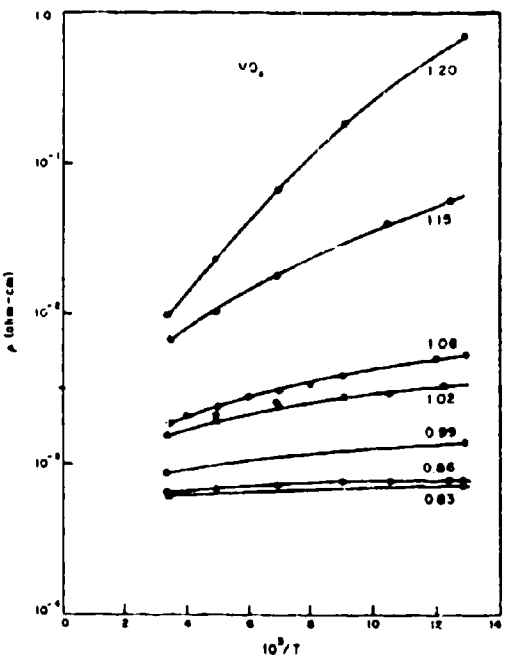
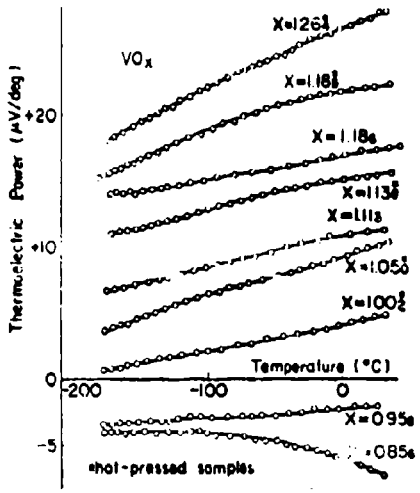


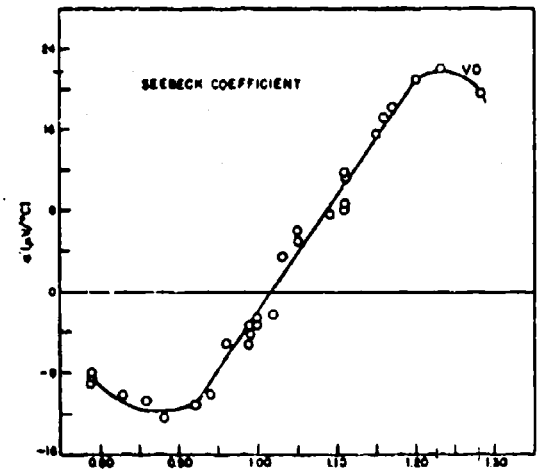
Electrical resistivity as a function of temperature and composition for sintered samples.

Banus et al.



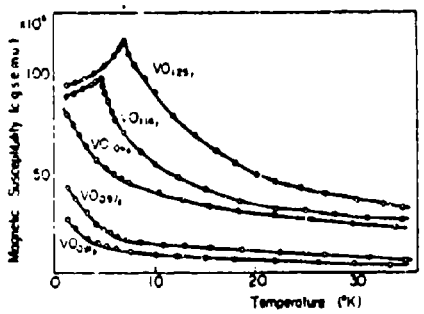
Thermoelectric power as a function of temperature for sintered VO_x

Kawano et al., B



Thermoelectric power as a function of composition in sintered VO_x

Banus et al.



Magnetic susceptibility as a function of temperature for sintered VO_x

awano et al., B

THE VANADIUM-OXYGEN SYSTEM

PHYSICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		VO_2				
Molecular Wgt.		82.94				
Density		4.69	g/cm^3			Donnay
Color		blue				Handbook
Symmetry		monoclinic				Donnay
Space Group		$P2_1/a$ Z-4				Donnay
Lattice Parameters	a_o	5.744	Å			Rao et al.
	b_o	4.520				
	c_o	5.376				
	β	122.6				
	V-V	2.65, 3.12	Å			Everhart & McChesney
Transition Temperature		68	°C	to rutile structure		Chamberland
Symmetry		tetragonal		(rutile)		Donnay
Lattice Parameters	a_o	4.559	Å		357	Rao et al.
	c_o	2.801				
	V-O	1.95				Bongers, Westman
	O-O	2.50, 2.87				
Temperature Coeff.	(1/a)(da/dT)	0.5	10^{-5}/°K		340-550	Bongers
	(1/c)(dc/dT)	3.6				
Melting Point		1818	°K			Cook, TPRC, p. 532
Specific Heat		0.157	cal/g °K		300	TPRC, Berglund & Guggenheim
		0.25			1700-1900	TPRC

THE VANADIUM-OXYGEN SYSTEM

PHYSICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Debye Temperature		750	°K		300	Berglund & Guggenheim, Derbenwick
Thermal Conductivity		65	mW/cm °K		300-360	Berglund & Guggenheim
Thermal Expansion Coefficient		24	10^{-6}/°K	monoclinic, single crystal, ‖ c-axis	68°C	Guntersdorfer
		‖-a ⊥-a 26 4.9	10^{-6}/°K	tetragonal, single crystal	137°C	Hazony & Perkins, Bongers
Young's Modulus		2	10^{12} dynes/cm^2	monoclinic	300	Guntersdorfer
ELECTRICAL PROPERTIES						
Dielectric Constant		E ⊥ a	E ‖ a			
Optic	ε_∞	10.0	9.7	reflectivity meas. at 1-90μ on single monoclinic crystal	300	Barker et al.
Static	ε_0	40.6	25.9			
Optic						
Monoclinic		5.6	5.54	at 0.3-6μ	300	Verleur et al.
Monoclinic		4.26		1000 Å film at 0.25 to 4μ	300	
Tetragonal		3.95		1000 Å film at 0.25 to 6μ	355	
Optic		0.6	1.2μ			
Monoclinic		8.5	9.5	single crystals & sputtered films	300	Derbenwick
Tetragonal		6	-1		350	
Optic		E ⊥ a	E ‖ a			
Tetragonal		3.77	4.17	single crystal at 0.25 to 3μ	355	Verleur et al.

THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Dielectric Constant						
Pressure Coeff.	$(1/\varepsilon)(d\varepsilon/dP)$	-2	10^{-6}/bar			Neuman et al.
Resistivity		5	Ω-cm	high purity, single crystal	293	Bongers, McChesney & Guggenheim, Bando et al., Ladd & Paul
		10^{-4}			341	
		5×10^{3}		single crystal	4	Austin & Turner
			f (Hz)			
		10^{-5}	0	single crystal, ‖-[100]	300	Kabashima et al.
		100	10^{3}-10^{8}			
		25	10^{10}			
	‖c-axis	‖a-axis				
	4×10^{-2}	10^{-2}	Ω-cm	epitaxial films on rutile	300	Koide & Takei
	2×10^{-3}	4×10^{-4}		monoclinic crystals	300	Everhart & McChesney
Temperature Coeff.	Ω-cm	TCR	Thickness			
	4.2	-0.036/°C	700 Å	sputtered films	300	Hensler et al.
	2.3	-0.106/°C	1000			
Pressure Coeff.	$d\rho/\rho dP$	-2	10^{-5} cm^2/kg	single crystal, $P = 5\times10^{3}$ kg/cm^2	293	Ladd & Paul, Guntersdorfer, Neumann et al.
		-3.5				

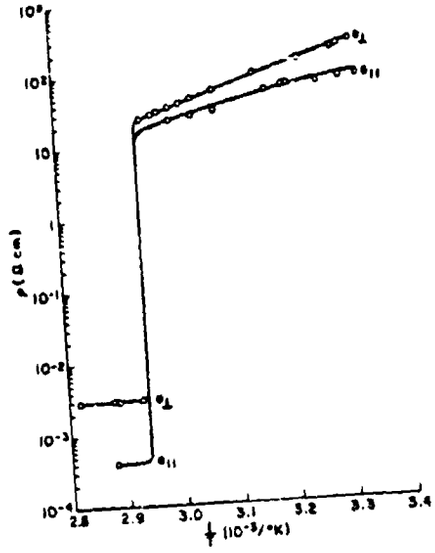
THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTIES	SYMBOL	VALUE	UNIT	NOTES	TEMP.(°K)	REFERENCES
Transition Temperature	T_c	68°C				Chamberland
Pressure Coeff.	dT_c/dP	+8.02	10^{-5}°K/kg cm^{-2}	single crystal, P= 4×10^4 kg/cm^2 dρ= 10^4 Ω-cm		Berglund & Jayaraman
		+5.90		high purity, single crystal, P= 8×10^3 kg/cm^2		Ladd & Paul, Neumann et. al.
Transition Time		20	nsec.	1600 Å thick film, sputtered on glass		Roach & Balberg, Cope & Penn
Mobility		0.05 0.01	cm^2/V sec	sputtered film, powder	273 370	Hensler, Kitahiro et al.
		0.6 15-20		single crystal, 1 Ω-cm	300 353	Barker et al.
Effective Mass						
Electron	m_n	0.5-4	m_o	metallic state, calc. from optical and electric meas.	>68°C	Barker et al., Berglund & Guggenheim
	m_{dn}	1.6-7		semiconducting state	<68°C	
	m_n	1-4				
	m_n	7.1		single crystal, sputtered films	>68°C	Hensler
		1			<68°C	
Energy Gap		0.6-0.7	eV	optical meas. at 0.3-6μ on a film, electrical meas. on a single crystal, photoemission meas. on a film	<68°C	Verleur et al., Heywang & Guntersdorfer, Powell et al.

THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTIES	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Energy Gap Pressure Coeff.	dE_g/dP	$\sim -10^{-6}$	eV/kg cm^{-2}	semiconducting state		Berglund & Jayaraman
Deformation Potential		8	eV	piezoresistance meas. on single crystal	300	Guntersdorfer
Photoemission Threshold		5.4 4.8	eV	5μ film	298 373	Powell et al.
Quantum Yield		7×10^{-3} 2×10^{-2}	electrons/proton		298 373	Powell et al.
Seebeck Coeff.		-21.1 -23.1	μV/°C	‖ c-axis ⊥ c-axis	75°C	Berglund & Guggenheim, Hensler
		-30 to -400			300	
		-900 -750		single crystal	293 333	Kitahiro & Watanabe, Bongers
		-130		700-1300 Å, single crystal, sputtered films	300	Hensler
Magnetic Susceptibility	X_g	0.88	10^{-6} cgs	single crystals	100-300	Barker et al., Hill & Martin
		⊥-c ‖-c				
		0.85 1.0 7.9 8.4	10^{-6} cgs	single crystal	293-340 340-373	Berglund & Guggenheim
Reflectivity		metallic		λ= 0.7-0.8μ	70°C	Mokerov & Rakov, Barker et al.
Emissivity		2.5 4.4 2.0	10^{-2} W/cm^2	single crystal	300 340 341	Boyle & Verleur

VO_2 - ELECTRICAL RESISTIVITY



Resistivity of single crystal VO_2 as a function of temperature, measured parallel and normal to the monoclinic a-axis.

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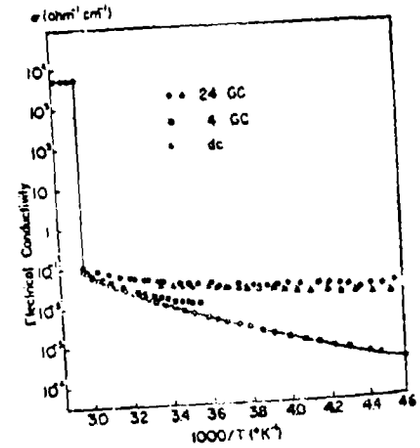
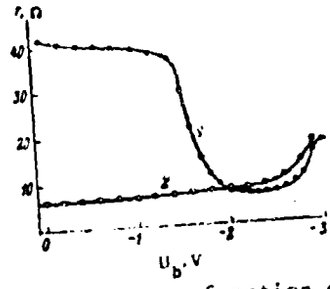
Everhart & McChesney



The dc and microwave conductivities of single crystals, as a function of temperature.

Kabashima et al.



Resistance as a function of bias voltage at 296°K.

1. Increasing voltage
2. Decreasing voltage

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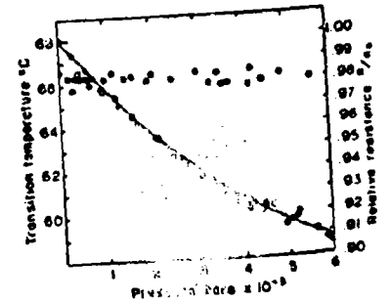
Valiev et al.



Pressure dependence of the transition temperature in single crystal VO_2 at 24.5°C

- ○ increasing pressure
- ◇ decreasing pressure
- ● resistance normalized to atmospheric pressure

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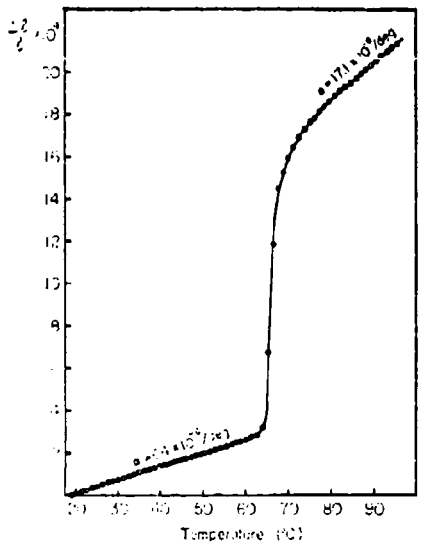
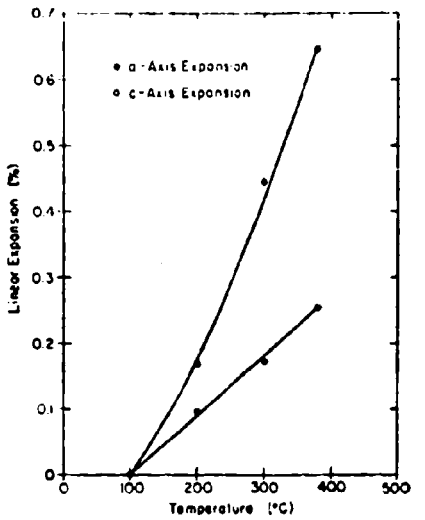
Neumann et al.

VO_2 - PHASE TRANSITION



Thermal expansion as a function of temperature for sintered VO_2

Kawakubo & Nakagawa



Thermal expansion of tetragonal VO_2 along two axes.

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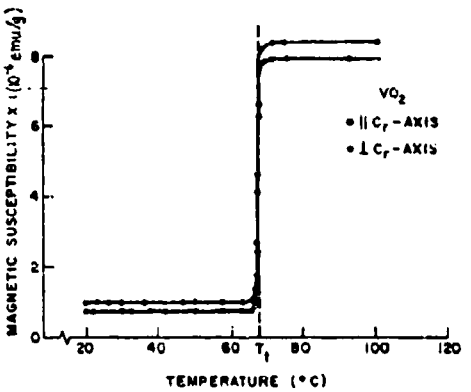

Magnetic susceptibility as a function of temperature in single crystal VO_2 near the transition temperature. Measurements are parallel and normal to the rutile c-axis.

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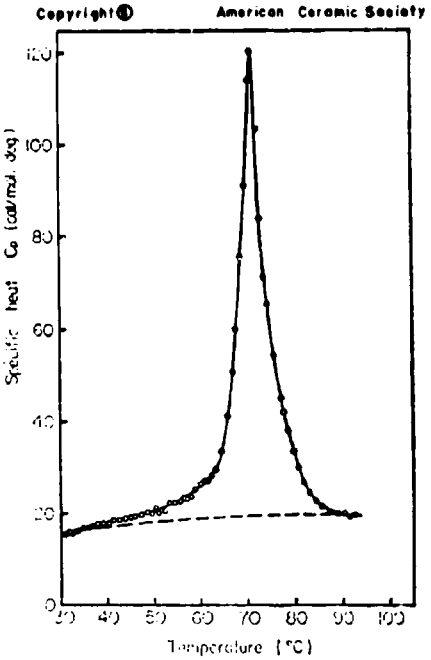
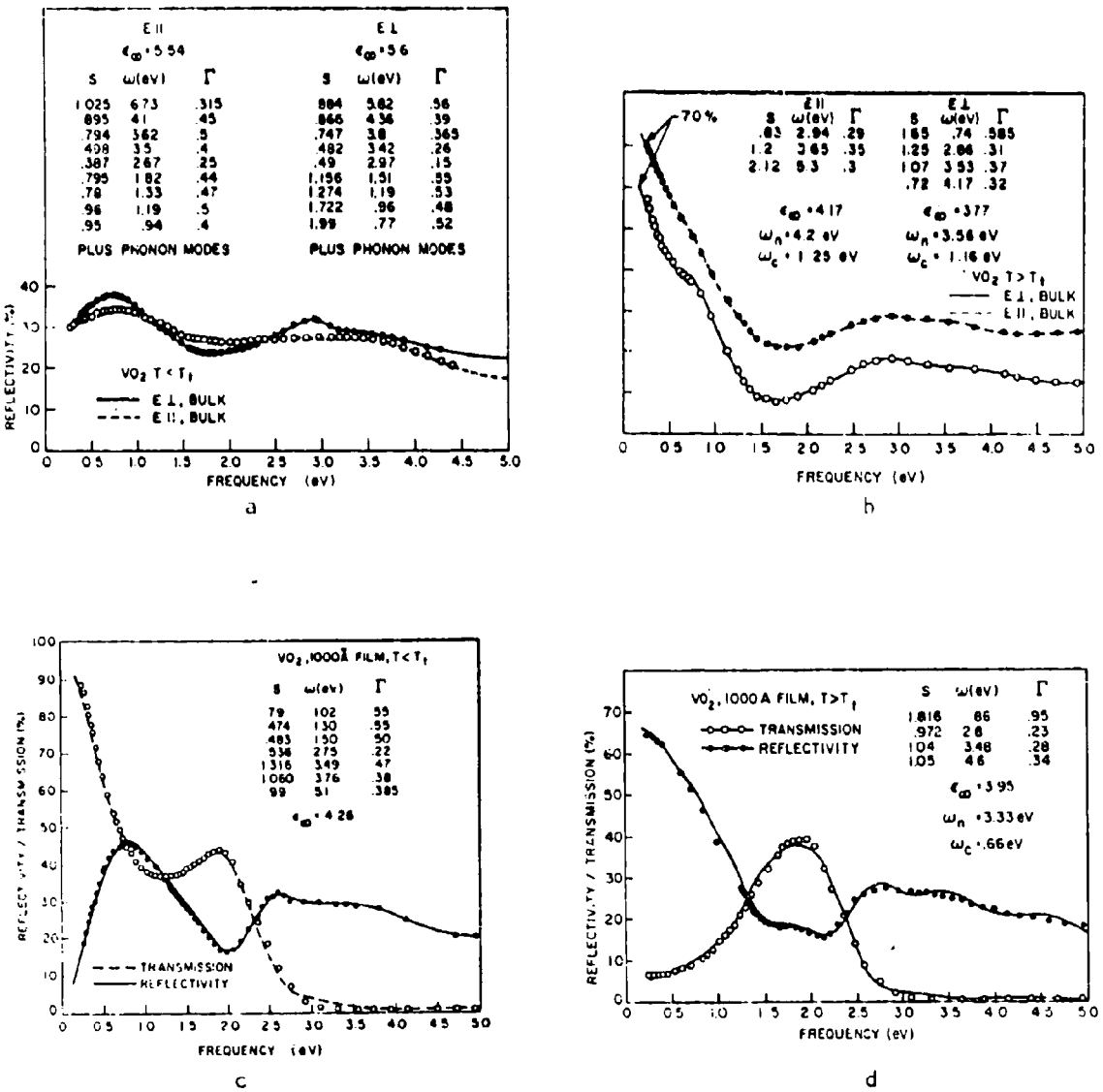


Specific heat as a function temperature for sintered VO_2

Kawakubo & Nakagawa

VO_2 - OPTICAL PROPERTIES



Reflectivity/Transmission data as a function of photon energy for single crystals and films of vanadium dioxide. The classical oscillator fit is shown at 300°K as well as slightly above the transition temperature, 355°K

a. bulk single crystals at 300°K
b. bulk single crystals at 355°K
c. 1000 Å film on sapphire substrate at 300°K
d. 1000 Å film on sapphire substrate at 355°K

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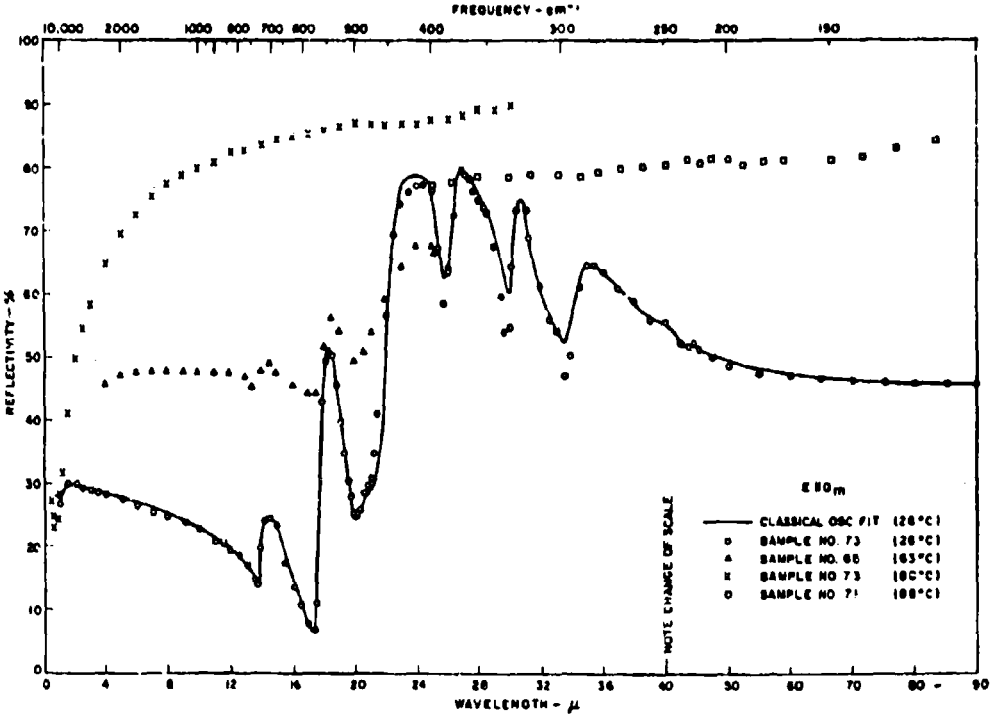
Verleur et al.

VO_2 - REFLECTIVITY



Reflectivity as a function of wavelength at three temperatures. The solid curve is a fit for data below the transition temperature, at 63°C, Data points marked by a triangle were taken on cooling.

Barker et al.

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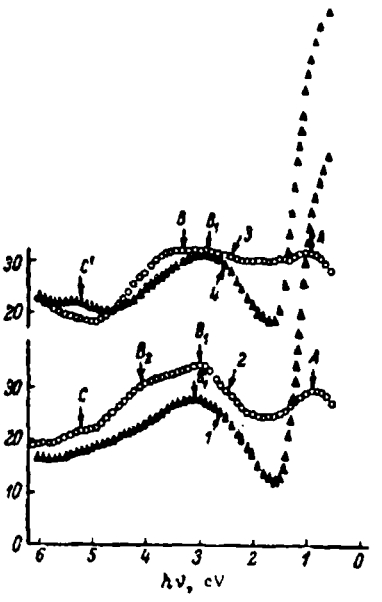
Reflectivity as a function of wavelength for single crystals, measured above and below the transition temperature.

1. $E \parallel c_r$ above 70°C
2. $E \perp a_m$ at 20°C
3. $E \parallel a_m$ at 20°C
4. $E \parallel c_r$ above 70°C

Structure above 2 eV is associated with electron transitions; below 2 eV the reflectivity is metallic.



Mokerov & Rakov

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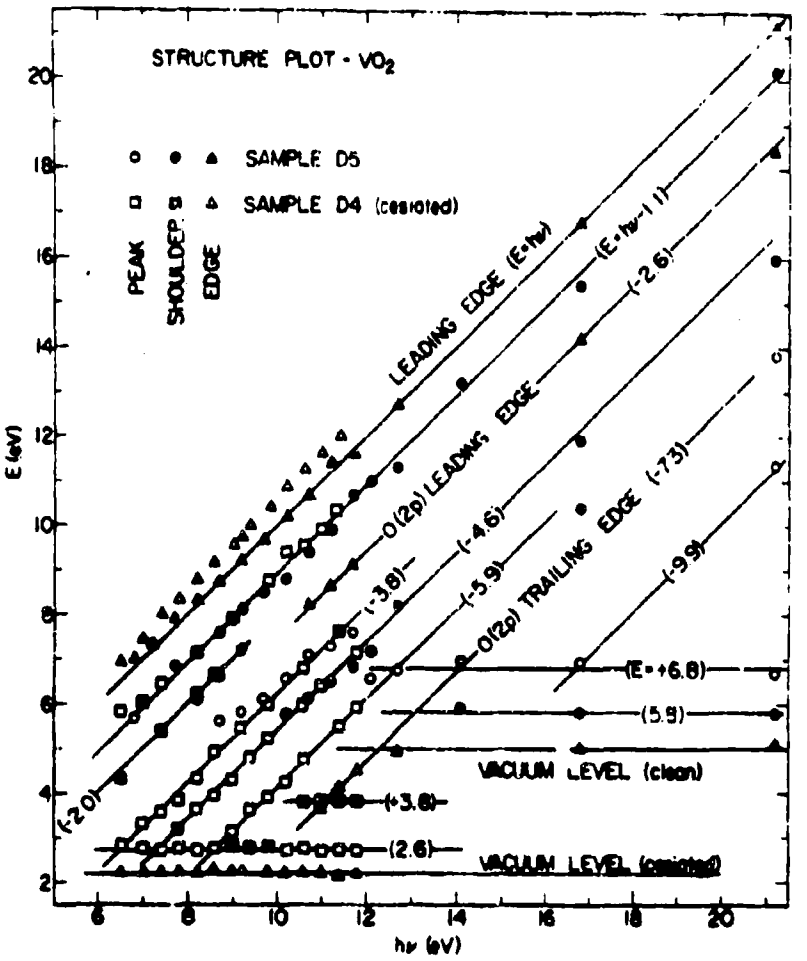
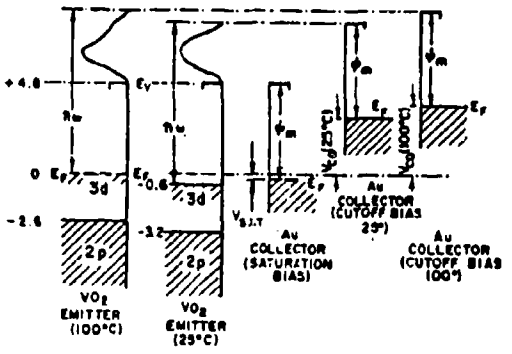
VO_2 - BAND STRUCTURE



Electron energy, E, is measured relative to the uppermost occupied level. The location of the structure relative to the uppermost occupied level is the same for V_2O_4 and V_4O_8 within the resolution of the photoemission.

Derbenwick



Energy level and bias relationships for VO_2 above and below the transition temperature. E_f is the Fermi level and E_v marks the vacuum level. The energy zero point is placed at the Fermi level.

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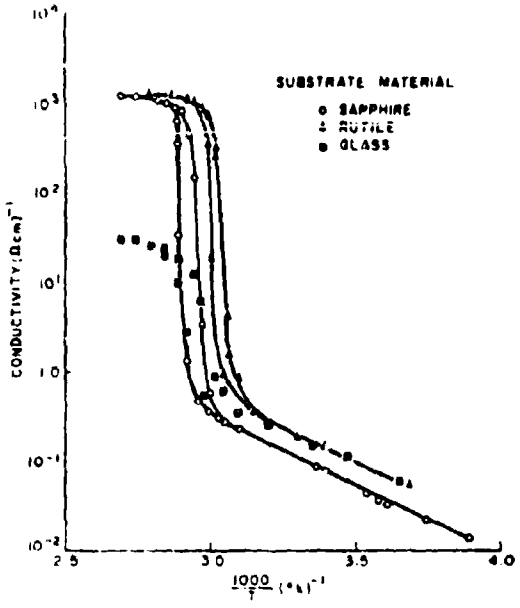
VO_2 - FILMS



Electrical Conductivity as a function of temperature for VO_2 films.

Curves show the effects of various substrates on the transition temperature.

Rozgonyi & Hensler

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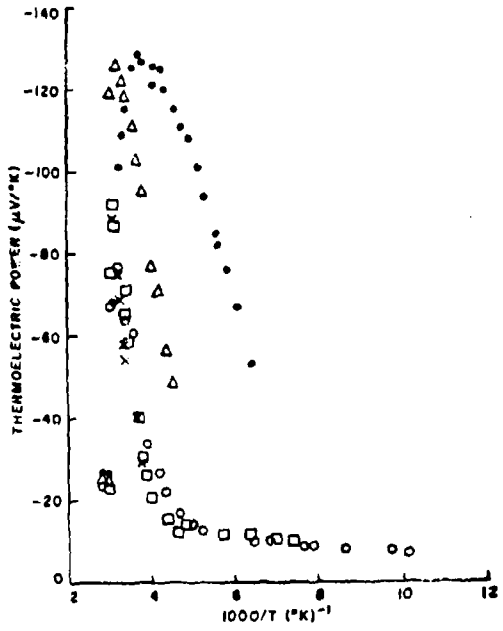

Thermoelectric power as a function of temperature for VO_2 films of varied thickness, deposited on various substrates.

×	Al_2O_3	670 Å thick
□	"	1500 Å
○	TiO_2	1500 Å
△	Al_2O_3	1300 Å
●	"	1300 Å

Hensler

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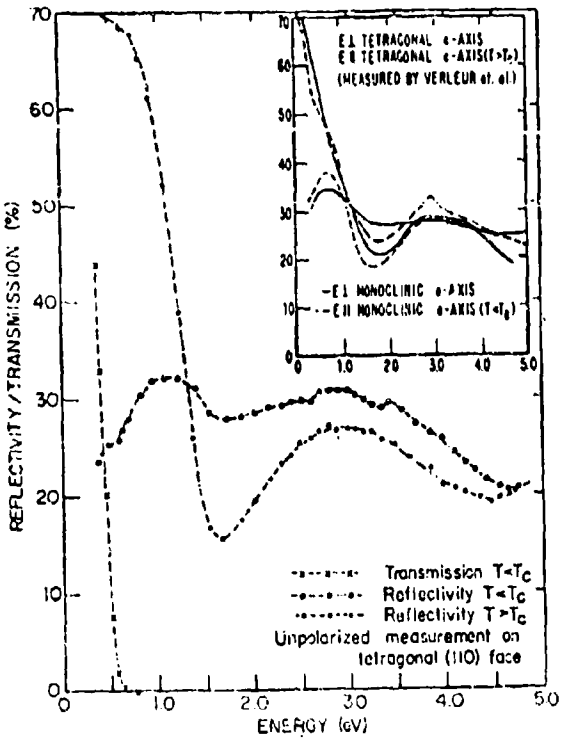
THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_2O_4				
Molecular Wgt.		165.884				
Density		4.4	g/cm^3			Cook
Symmetry		monoclinic			<70°C	Chamberland, Minomura & Nagasaki
Lattice Parameters	a_o	5.753	Å		335	Chamberland, Minomura & Nagasaki
	b_o	4.524				
	c_o	5.382				
	β	122.62°				
Symmetry		tetragonal		(rutile)	>70°C	Minomura & Nagasaki, King & Suber
Lattice Parameters	a_o	4.54	Å		344	Minomura & Nagasaki
	c_o	2.85				
Coefficient of Expansion		5.4	10^{-6}/°K	(tetragonal)		King & Suber
Shift in Coefficient		-1	10^{-4}/°K		67°C	Minomura & Nagasaki
Melting Point		1547	°C			TPRC, p. 532, Cook
Specific Heat		0.18	cal/g°K		300	TPRC, p. 532
		0.25			1700	
		0.25			1800	

THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Dielectric Constant						
Optical	ε_∞	9		tetragonal, E||c-axis	353	Barker et al.
Resistivity		10^{-4} 10	Ω-cm	single crystal, high quality, oriented ||c-axis	>339 <339	Ladd & Paul
Transition Temperature		66	°C			Ladd & Paul
Pressure Coeff.	dT_c/dP	6	10^{-5} °K/bar	P= 8 kbars		Ladd & Paul
Resistivity		10^{-2}	Ω-cm	amorphous film, rf-sputtered on substrate at 135°C	300	MacKenzie
Energy Gap	E_g	0.65	eV	transmission meas. on single crystal	300	Ladd & Paul

V_2O_4 - REFLECTIVITY

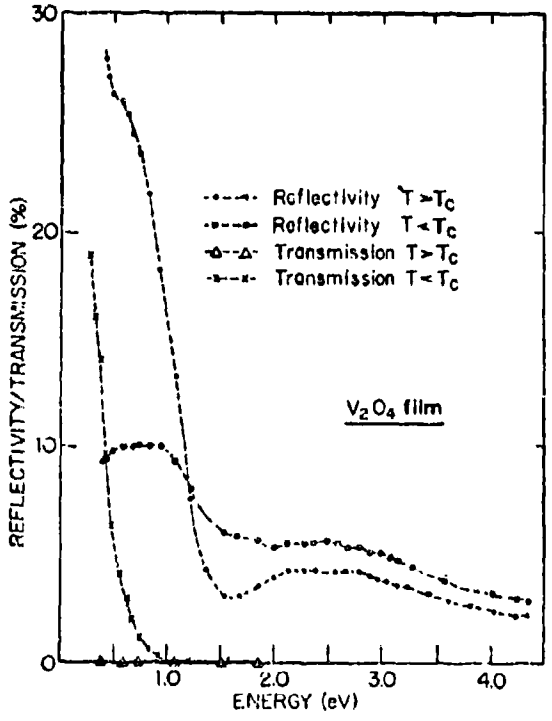


Reflectivity/Transmission as a function of wavelength in a single crystal, above and below the transition temperature, (300 and 360°K). Transmission is also shown for a thin sample at 300°K

Fan & Paul

Reflectivity/Transmission of a single crystal, epitaxial film, grown by vapour transport. Data are taken above (350°K) and below (300°K) the transition temperature.

Fan & Paul



THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_5O_9		$VO_{1.8}$		Kosuge[B]
Molecular Wgt.		398.71				
Symmetry		triclinic				Donnay
Lattice Parameters	a_o	7.004	Å			Donnay
	b_o	7.825				
	c_o	5.465				
	α	97°39'				
	β	109° 2'				
	γ	94° 6'				
Density		4.72	g/cm^3			Donnay
Electrical Resistivity		10^{-3}	Ω-cm	single crystal	130-300	Okinaka et al.[D]
		10^3-10^4			125	
Transition Temperature		130	°K	single crystal		Okinaka et al.[D]
Seebeck Coeff.		-10 to -20	μV/°K	single crystal	130-300	Okinaka et al.[D]
		-200			125	
		-800			110	
Magnetic Susceptibility	X_g	10	10^{-6} cgs	single crystal	77-140	Nagasawa et al.[A]
		45			140	Kosuge [B]
		28			265	
Néel Temperature		162	°K	sintered		Kosuge et al.[A]

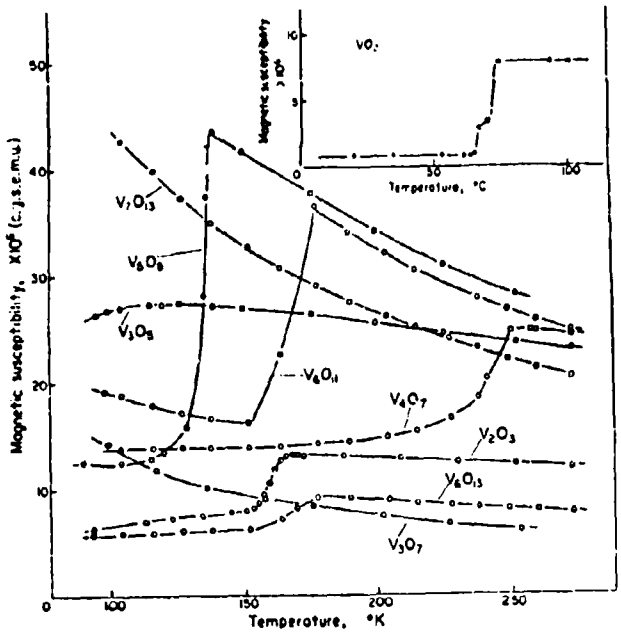
THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP.(°K)	REFERENCES
Formula		V_6O_{13}		$VO_{2.16-2.17}$		Kosuge[B]
Molecular Wgt.		513.652				
Melting Point		708	°C			Kosuge[B]
Symmetry		monoclinic		$V_{12}O_{26}$		Donnay
Lattice Parameters	a_o	11.90				Donnay
	b_o	3.671				
	c_o	10.122				
	β	100°52'				
Expansion Coeff.		-1.62	10^{-4}/°K	sintered	80-173	Kosuge et al.[B]
		+1.14	10^{-5}/°K		173-300	
Electrical Resistivity		10^3	Ω-cm	sintered	300	Kachi et. al.
		$3x10^5$			156	
		$2x10^4$			157	
		$2.5x10^6$			100	
Transition Temperature		156	°K	electrical meas.		
		154		magnetic meas.		
Pressure Coeff.	dT_c/dP	-1.06	10^{-4} °K/bar	single crystal		Kosuge et al.[B]
Magnetic Susceptibility	X_g	6	10^{-6} cgs	sintered	77-150	Kosuge et al.[A,B]
		9			175	
		8			280	
Néel Temperature		155	°K			Kosuge et al.[A]

THE VANADIUM-OXYGEN SYSTEM

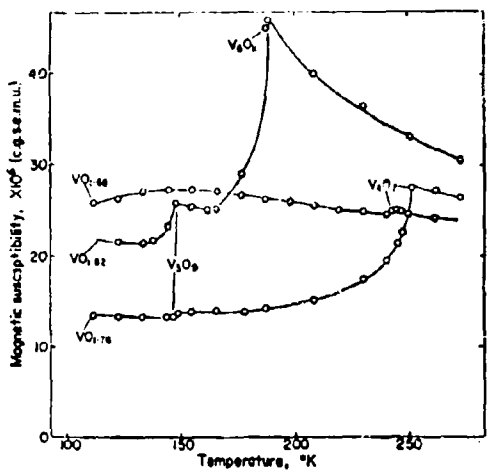
PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_6O_{11}		$VO_{1.83}$		Kosuge[B]
Molecular Wgt.		481.652				
Electrical Resistivity		10^{-1} 10^{2}	Ω-cm	single crystal	177-300 177	Okinaka et al.[C]
Transition Temperature		177	°K			Okinaka et al.[C]
Seebeck Coeff.		-10 -900	μV/°K	single crystal	177-300	Okinaka et al.[C]
Magnetic Susceptibility	X_g	20 36 31	10^{-6} cgs	single crystal, T_c = 170°K	77 170 250	Nagasawa et al.[B], Kosuge[B]
Formula		V_7O_{13}		single crystal		Okinaka et al.[C]
Electrical Resistivity		10^{-3}	Ω-cm		120-300	
Seebeck Coeff.		-1	μV/°K		120-300	
Magnetic Susceptibility	X_g	44 22	10^{-6} cgs		100 250	Kosuge[B]
Formula		V_4O_7		single crystal		Okinaka et al.[E]
Electrical Resistivity		10^{-2} $2x10^{-3}$ 10^{2}	Ω-cm		300 250 200	
Seebeck Coeff.		-10 -230	μV/°K		250-300 200	
Transition Temperature		250	°K			
Magnetic Susceptibility	X_g	14 24	10^{-6} cgs		100-175 250-280	Kosuge[B]

VANADIUM DIOXIDES



Magnetic susceptibility as a function of temperature for a series of vanadium dioxides.

Kosuge, B



Magnetic susceptibility as a function of temperature, employed for the phase identification of a series of non-stoichiometric V_2O_4 compounds.

Kosuge, B

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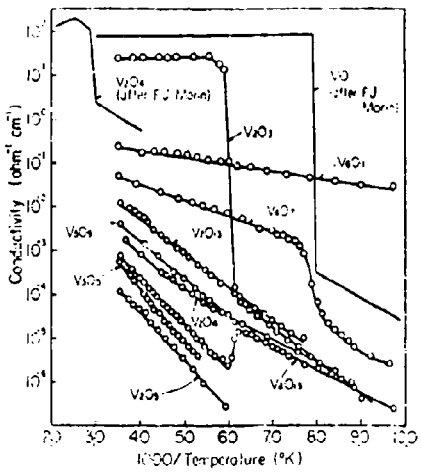
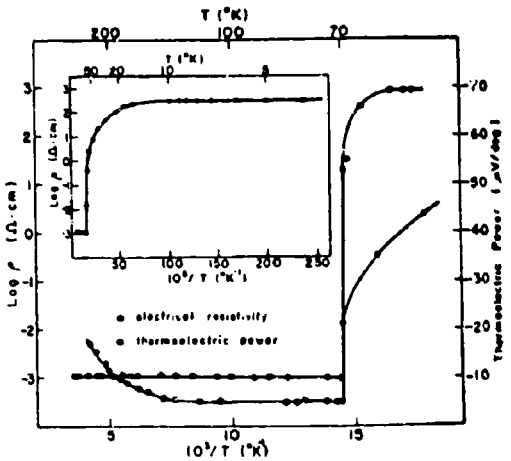
VANADIUM DIOXIDES



Electrical conductivity as a function of temperature for a series of vanadium oxides.

Kachi et al.



Electrical resistivity and thermoelectric power for V_8O_{15} as a function of temperature. The insert shows the electrical resistivity-temperature curve down to 4°K

Okinaka et al., B

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THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_2O_5				
Molecular Weight		181.88				
Density		3.357	g/cm^3	single crystal	298	Kennedy et al.
		2.42-2.69		amorphous		
Color		pale yellow		transparent		Kenny et al.
Cleavage		(100)		acicular habit		Donnay
Symmetry		orthorhombic				Donnay
Space Group		Pnm2 Z-2				Donnay
Lattice Parameters	a_o	11.510	Å			Bachmann et al.
	b_o	4.369				
	c_o	3.563				
Melting Point		668	°C	single crystal, loses oxygen on heating in vacuo at 600°C		Kennedy et al.
		676				Kosuge, [B] Kimizuka et al.
Specific Heat		0.167	cal/g°K		300	TPRC, p. 534
		0.227			950	
Thermal Expansion Coefficient		2	10^{-6}/°K	|| a-axis	25-600°C	Kennedy et al.
		55.4		|| b-axis		
		8		|| c-axis		
ELECTRICAL PROPERTIES						
Dielectric Constant						
Optical	ε_∞	~ 4				Kenny et al.

THE VANADIUM-OXYGEN SYSTEM

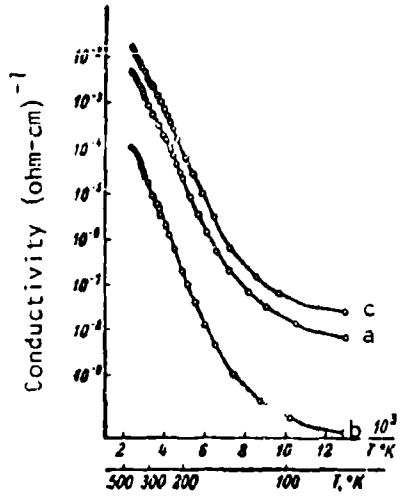
PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Dielectric Constant						
Static	ε_0	6.89		pressed powder at 6 GHz	300	Kiriashkina et al.
Resistivity	a	b	c (axes)			
	170	4700	670 ohm-cm	single crystal	298	Kennedy et al.
	5×10^8	10^{10}	2×10^8	single crystal	100	McCulloch
	10^3	2×10^3	5×10^2	platelets grown at 700°C, laminar with mirror surface	300	
	10^8	10^{10}	3×10^7	high purity, single crystal	77	Volzhenskii & Pashkovskii, Ioffe & Patrina, Patrina & Ioffe
	2×10^4	10^5	200		300	
	120	10^4	50		450	
	1.6	4	0.4 10^3 ohm-cm	single crystal	293	Allersma et al.
		25	ohm-cm	liquid in air	670°C	
		7		liquid in argon		
		10^5		high density, amorphous film	300	
		10^6		low density, amorphous film	300	
		1.1×10^6		0.5-5μ thick, amorphous film	300	Kennedy et al.
		3×10^4	ohms	P <100 kbars	300	Minomura & Drickamer
		10^3		P=100-105 kbars		
		4×10^4		P >105 kbars		
		10^4		P >300 kbars		
Mobility		5	cm^2/V sec	high purity, macrocrystalline	300	King & Suber

THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE		UNIT	NOTES	TEMP. (°K)	REFERENCES
Mobility	a	b	c (axes)				
	10^{-2}	3×10^{-4}	5×10^{-2}		high purity, single crystal	300	Volzhenskii & Pashkovskii
	10^{-2}	10^{-2}	10^{-1}			440	
Energy Gap	$E_{\parallel-c}$	$E_{\parallel-a}$					
	2.34	2.36		eV	optical meas. on high purity single crystal	300	Kenny et al.
	2.49 2.30	2.54 2.32			single crystal, optical meas. at 0.47-0.56 μ	0 300	Bodo & Hevesi
Temperature Coefficient	dE_g/dT	-6.1	-7.3	10^{-4} eV/°K		293-653	Bodo & Hevesi
Seebeck Coefficient	a	b	c (axes)				
	-5.8 -9 -8.4	-6.4 -8.2 -8	-8 μV/°K -10 -9		high purity, single crystal, max. at 250°K	180 250 420	Volzhenskii & Pashkovskii
		-1000		μV/°K	single crystal	300	Ioffe & Patrina
Magnetic Susceptibility	χ_g	+0.4		10^{-6} cgs	yellow form	300	Tourky et al.
		+1.1				100-400	Roch
		H ⊥ b-axis	H ∥ b-axis		single crystal plates, H=5 kOe	77-300	Khan et al.
		0.3	0.2 (10^{-6})				
OPTICAL							
Transmission		80		%	0.8 μ thick film λ = 0.52 μ		Sinclair et al.

THE VANADIUM-OXYGEN SYSTEM

PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Refractive Index		Wavelength (μ)				
	0.55-0.75	0.6708	0.5893			
	n_a	2.07	2.70	2.89	single crystal, birefringent	300	Kenny et al., King & Suber
	n_b	1.97	2.07	2.10		
	n_c	2.12	2.45	2.55		



Electrical conductivity as a function of temperature in single crystal V_2O_5 along the three crystal axes.

Volzhenskii & Pashkovskii, Ioffe & Patrina

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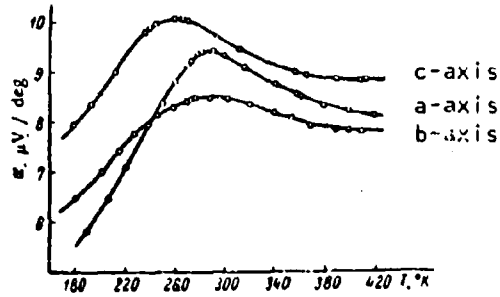

Thermoelectric power in single crystal V_2O_5 grown under 5 atm. oxygen pressure. Maximum at 250°K for thermal emf along the c-axis.

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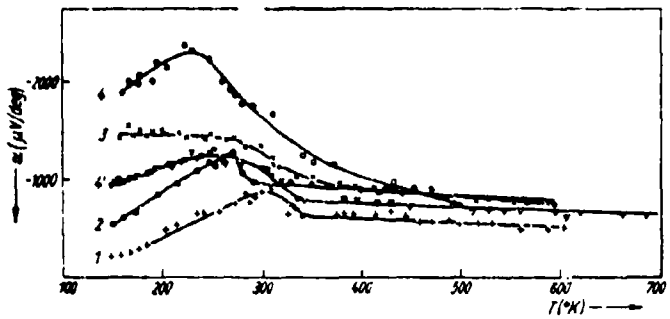

Thermoelectric power as a function of temperature for V_2O_5 single crystals. #4' is annealed at 800°K

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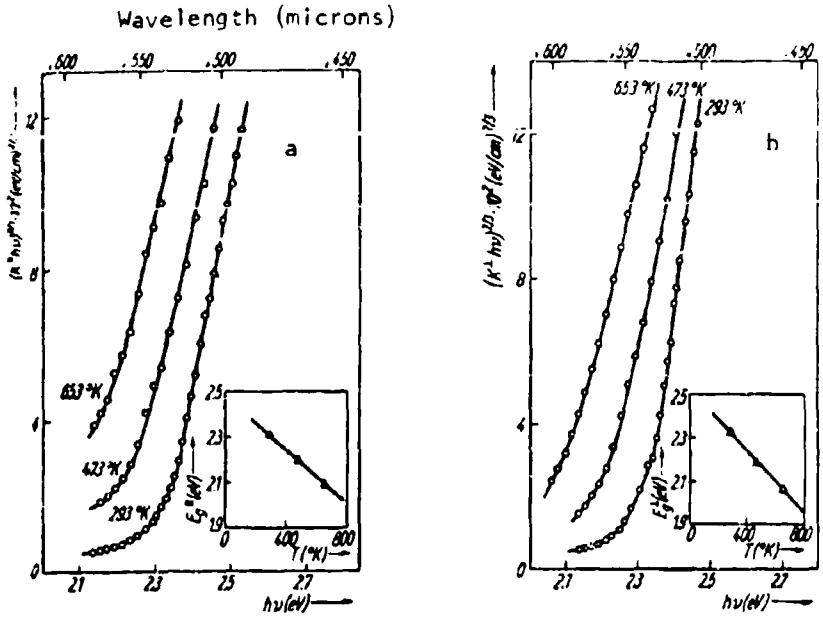
V_2O_5 - OPTICAL PROPERTIES



Absorption edge as a function of wavelength in single crystals of V_2O_5 at three temperatures.

a. E parallel to c-axis
b. E normal to c-axis

Bodo & Hevesi

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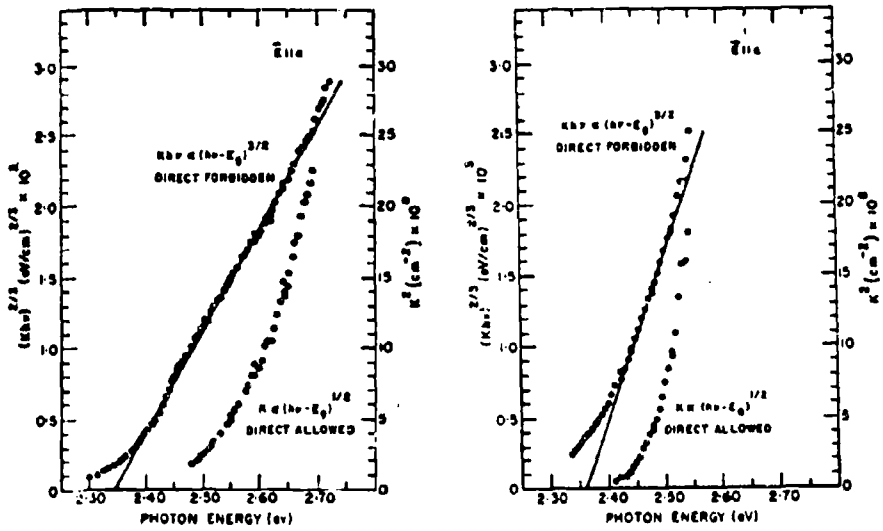

Absorption edge as a function of wavelength in single crystals of V_2O_5 at 293°K.

Kenny et al.

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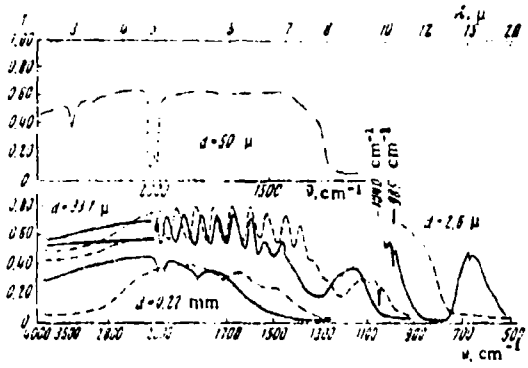
V_2O_5 - OPTICAL PROPERTIES

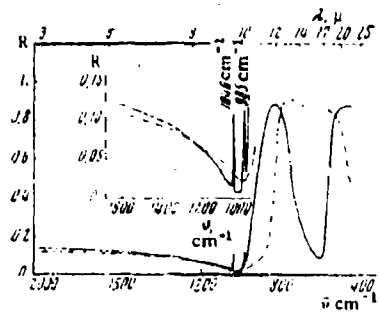


Transmission spectra of single crystals at 300°K.

------ E ∥ a

—·—·— E ∥ b

——— E ∥ c



Reflectance spectra of single crystals; spectra in the narrow band region are shown in the insert.

——— E ∥ a

---------- E ∥ c

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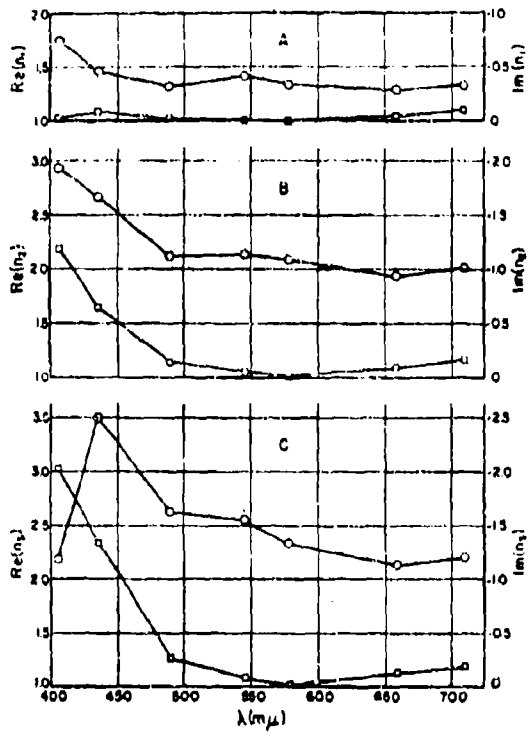
Hevesi et al.

V_2O_5 - OPTICAL PROPERTIES



Optical constants of single crystal V_2O_5 at 300°K (monoclinic phase)

- o The three refractive indices as a function of wavelength
- □ Imaginary components

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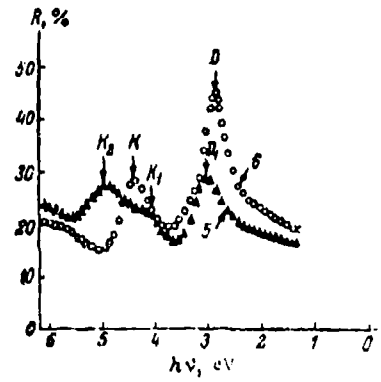
Journal of the Optical Society of America



Reflectivity as a function of wavelength for single crystals at 300°K

5. E ∥ c-axis, 6. E ∥ a-axis

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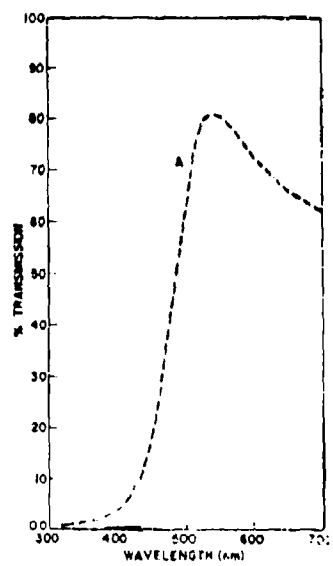

Transmission as a function of wavelength for a sputtered V_2O_5 film, 0.8 μ thick.

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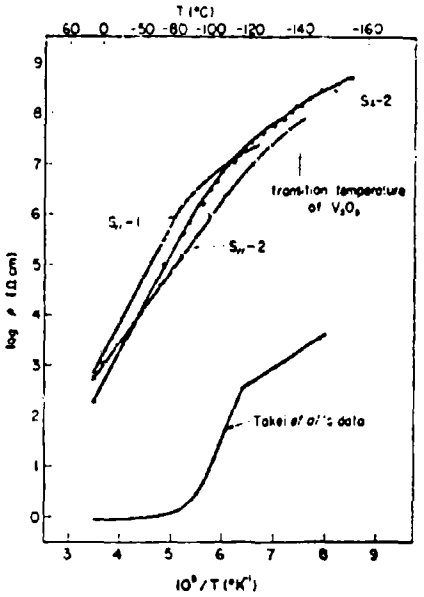
THE VANADIUM-OXYGEN SYSTEM

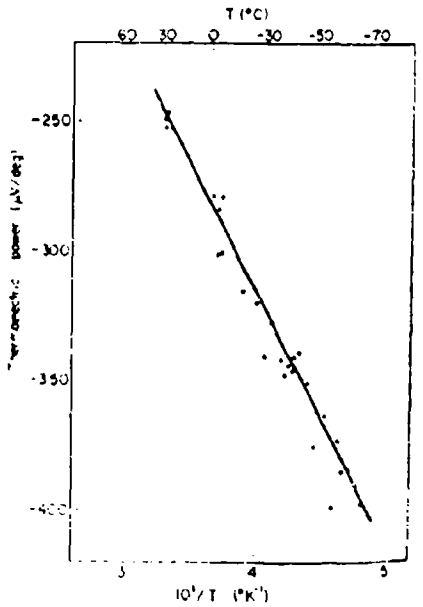
PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_3O_5		$VO_{1.65-1.67}$		Kosuge [B]
Molecular Weight		232.826				
Density		4.55	g/cm^3			Donnay
Symmetry		monoclinic		Z-4		Donnay
Lattice Parameters	a_o	9.835	Å			Donnay
	b_o	5.031				
	c_o	6.974				
	β	109° 28'				
Electrical Resistivity		250	ohm-cm	single crystal, meas. ⊥ growth-axis, slightly anisotropic, no transition	300	Okinaka [A] et al.
		10^6			185	
		2×10^8			115	
		2×10^3		sintered	300	Kachi et al.
		2×10^5			185	
Seebeck Coefficient		-250	μV/°K	single crystals	300	Okinaka [A] et al.
		-400			200	
Magnetic Susceptibility	X_g	24	10^{-6} cgs	single crystals	250	Nagasawa [B] et al.
		30			77	

V_3O_5 - ELECTRICAL PROPERTIES



Electrical resistivity as a function of temperature for single crystal V_3O_5 Two samples were measured; from 250 to 300°K by a four point method and below 250°K by a two point method. Measurements were made as indicated, parallel and normal to the growth axis.

Okinaka et al.



Thermoelectric power as a function of temperature for single crystals.

Okinaka et al.

THE VANADIUM-OXYGEN SYSTEM

PHYSICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Formula		V_2O_3				
Molecular Wgt.		149.88				
Density		5.05	g/cm^3	monoclinic		Donnay
Color		black				Handbook
Symmetry		monoclinic				Donnay
Lattice Parameters	a_o	13.88	Å	<160°K		Donnay
	b_o	4.98				
	c_o	8.57				
	β	91°36'				
	V-V	2.745	Å	face (a-c plane)		Dernier & Marezio
	V-V	2.987		edge		
Symmetry		hexagonal		α-corundum		Donnay
Lattice Parameters	a_o	4.948	Å			McWhan & Rice, Nakahira et al, Newnham & de Haan
	c_o	13.97				
	V-V	2.700		face		Dernier & Marezio
	V-V	2.872		edge		
Density		4.98	g/cm^3	single crystal		Zhuze et al. [A]
Melting Point		2050	°C			Stringer
Specific Heat		0.165	cal/gr °K		300	TPRC, p. 530
		0.24			1700	
		0.25			1800	

THE VANADIUM-OXYGEN SYSTEM

PHYSICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Thermal Expansion		~-2	10^{-4}/°K	hot pressed at 1100°C	173°C	Foex
		~1	10^{-5}/°K		300-800°C	
ELECTRICAL PROPERTY						
Dielectric Constant						
Static	ε_o	15(±20%)		polycrystalline at 1 MHz	53	MacMillan, p. 18
		18		$V_2O_{3.7}$ pressed powder, ρ_{300}= 50 Ω-cm at 10 GHz	<160	Samokhavalov
		36				
Optical	ε_∞	~5		single crystal	>T_c	Zhuze et al.[B]
Electrical Resistivity		1.3×10^{-4}	Ω-cm	high purity, single crystal	300-170	Goodman
		10^5			168	
		10^7			115	
	∥-c plane	⊥ ∥-a plane				
	3×10^{-4}	1×10^{-4}		single crystal	285	MacMillan
	5.6×10^{-4}	6.3×10^{-4}		single crystal	273	Feinleib & Paul
	10^4				150	
	10^5				120	
	12×10^{-4}				500	
	21				600	
	26				700	
	29				800	
	10^4			amorphous, sputtered film	<170	MacKenzie
	10^{-2}				>170	

THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Electrical Resistivity						
Temperature Coeff.	$\rho(T)/\rho(0°C)$	$0.36+2.3\times10^{-3}T(°K)$		single crystal	150-350	Feinleib & Paul
		‖-c ‖-a				
Pressure Coeff.	$d\rho/dP$	-4.3 -8.8	10^{-6} Ω-cm/kbar	P=6 kbar	300	
		‖-a				
Volume Coeff.	$(1/\rho)(d\rho V/dV)$	42 20		P=1 bar P=25 kbar	300	McWhan & Rice
Transition Temperature	T_c	172±4	°K	high purity, single crystal		Goodman, McWhan & Rice, Morin
Pressure Coeff.	dT_c/dP	-4.1	°K/kbar	P=15 kbar, single crystal	150	Austin
		-3.78		P=6 kbar		Feinleib & Paul
		-3.1		P=160 kbar	77-500	Minomura & Nagasaki
		a b c (axes)				
Stress Coeff.	dT_c/dS	-6.8 -4.1 -0.5	°K/kbar	single crystal	300	Feinleib & Paul
Mobility						
Hole	μ_p	0.55 0.40	cm^2/V sec	single crystal	200 300	Zhuze et al. [A]
Temperature Coeff.		$T^{-0.7}$				
Hole	μ_p	0.6 0.2			300 700	Austin & Turner
Hole	μ_p	1.5×10^{-4}		single crystal	125	MacMillan

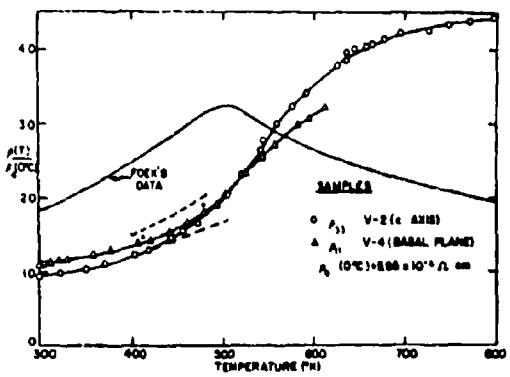
THE VANADIUM-OXYGEN SYSTEM

ELECTRICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
Effective Mass	m^*	45-50	m_o	single crystal	$>T_c$	Feinleib & Paul, Adler & Feinleib
		11		optical meas. on single crystal	$>T_c$	Zhuze et al.[B]
Mean Free Path		2	Å			Feinleib & Paul, Adler & Feinleib
Energy Gap		0.1	eV	optical meas.	77	Feinleib & Paul, Adler & Feinleib,
		0.12-0.18		electrical meas.	150-170	Barker & Remeika
Pressure Coeff.	dE_{g_o}/dP	-4.4	10^{-6} eV/bar	single crystal		Feinleib & Paul, Austin
Seebeck Coeff.	$Q_{\parallel}$	10.5	μV/°K	single crystal	285	MacMillan
	$Q_{\perp}$	3.2				
	Q	+350 -400		p-type n-type	100 100	
	$Q_{\parallel}$	~12 <-5			170-500 100-150	Austin & Turner
Magnetic Susceptibility	X_g	$\sim 10^{-7}$	cgs	single crystal	>170	MacMillan
		3.8 6.4	10^{-6} cgs	pressed powder	90 293	Bogdanova & Loginov
		$X_{\parallel}$ / $X_{\perp}$ 6.9 / 5.9 11.2 / 12.2	10^{-6} cgs	single crystal	<170 >170	Carr & Foner, Nakahira et al.
		12.42 / 12.58 11.24 / 10.88		single crystal	300	Arnold & Mires, Gossard & Menth

THE VANADIUM-OXYGEN SYSTEM

OPTICAL PROPERTY	SYMBOL	VALUE	UNIT	NOTES	TEMP. (°K)	REFERENCES
			Wavelength (μ)			
Transmission		0 maximum	0.2-20 6		300 77	Feinleib & Paul, Barker & Remeika
Refractive Index		1.84 1.67 1.95 6.8 8.8	0.4 1.0 2.0 10.0 20.0	single crystal	300	Zhuze et al.[B]

V_2O_3



Electrical resistivity as a function of temperature to 800°K for single crystals.

ρ_{33} measured along c-axis

ρ_{11} measured in basal plane

Foex's data on sintered bars are included.

Feinleib & Paul

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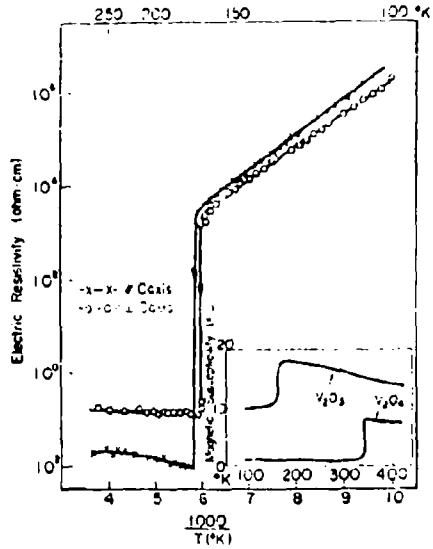
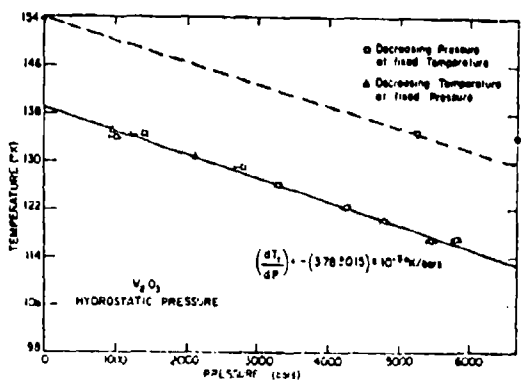


Resistivity as a function of temperature in single crystals.

Kosuge, A



Transition temperatures as a function of hydrostatic pressure in single crystals.

Feinleib & Paul

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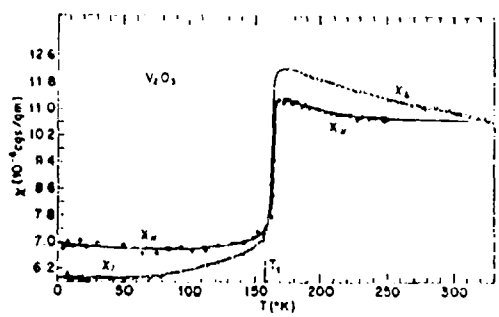

Magnetic susceptibility as a function of temperature in single crystals, parallel and normal to the basal plane.

Carr & Foner

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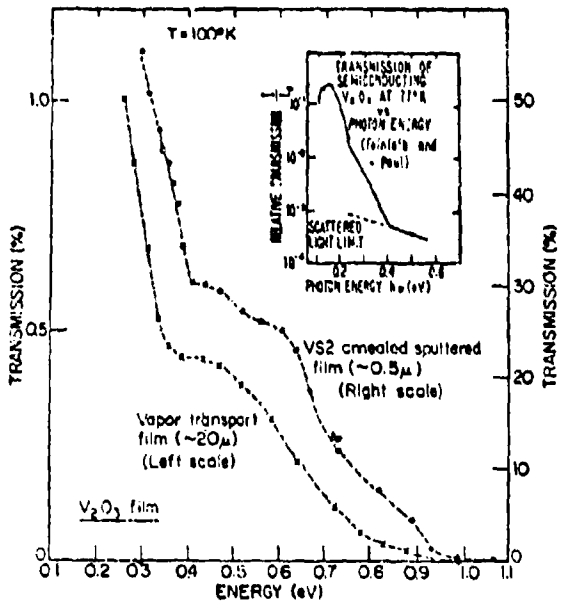
V_2O_3 - OPTICAL PROPERTIES

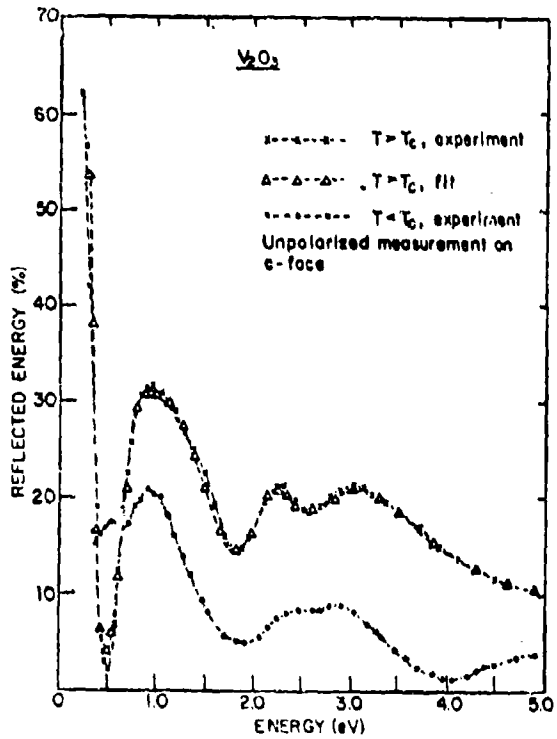


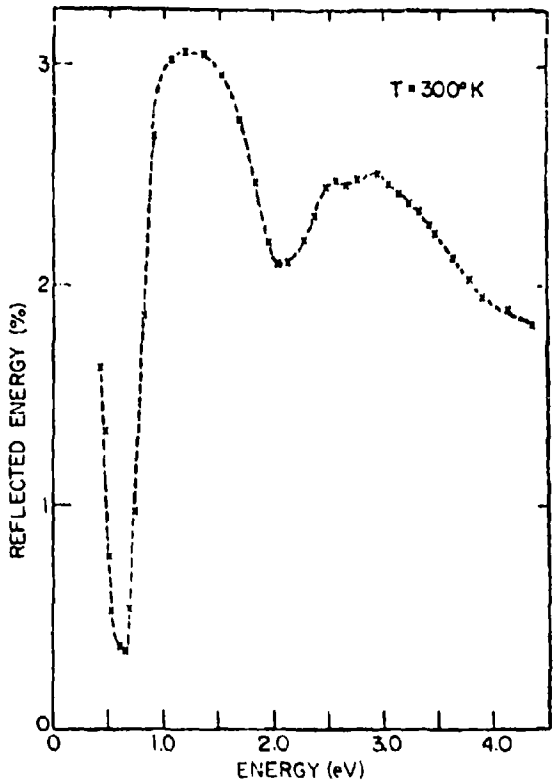
Low temperature transmission of a single crystal, epitaxial V_2O_3 film grown by vapour transport and of an annealed, sputtered film. Data from these two films are compared with transmission from a single crystal as reported by Feinleib and Paul.

Fan & Paul

Reflectivity of a single V_2O_3 crystal, above and below the transition temperature.

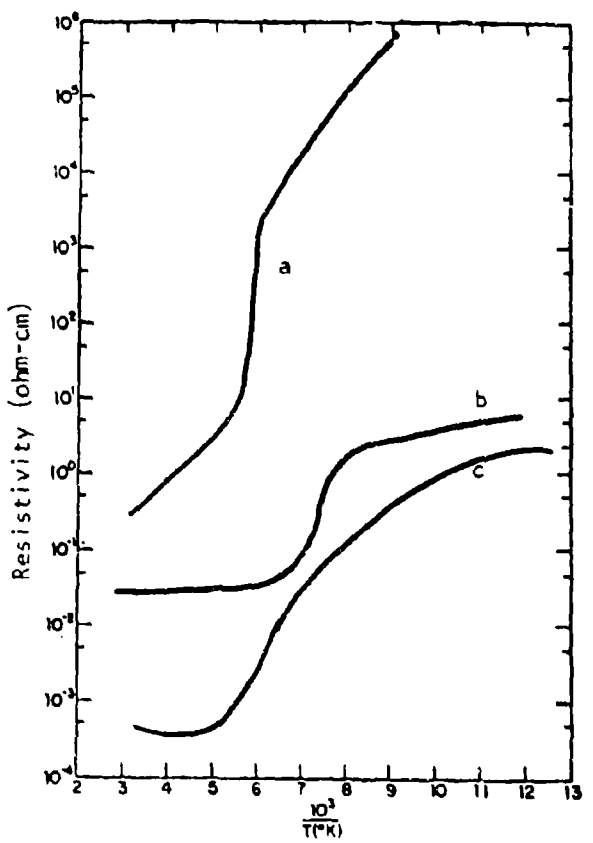
Fan & Paul





Reflectivity as a function of wavelength for a single crystal, epitaxial film. The substrate is single crystal alumina with the c-axis normal or parallel to the substrate plane.
T_1 = 800°C, T_2 = 60°C
Measurements in the infrared and visible are made above the transition temperature.

Fan & Paul



Electrical resistivity as a function of temperature for V_2O_3 films.

a. sputtered, polycrystalline film, about 0.55μ thick, alumina substrate, annealed at 600°C
c. similar film but showing great difference in resistivity

b. single crystal, epitaxial film, grown by vapour transport on alumina substrate

Fan & Paul

Crystal Structure, Transition Temperature and Conductivity in $V_{1-x}Ti_xO_2$

Composition	Monoclinic (25°C)				Rutile		Transition Temp. (°C)	Conductivity at 40°C $(ohm\text{-}cm)^{-1}$
x	a_o	b_o	c_o	β	a_o	c_o		
0.00	5.744	4.520	5.376	122.6	4.559	2.801	69	0.8
0.02	5.729	4.530	5.364	122.3	-	-	65	1.2
0.05	5.727	4.560	5.390	122.5	4.545	2.844	63	-
0.10	5.716	4.499	5.424	122.0	4.537	2.868	60	5.8
0.20	5.704	4.490	5.448	121.3	4.539	2.891	58	4.7
0.40	4.833	4.380	5.530	97.9	4.546	2.894	48	0.3

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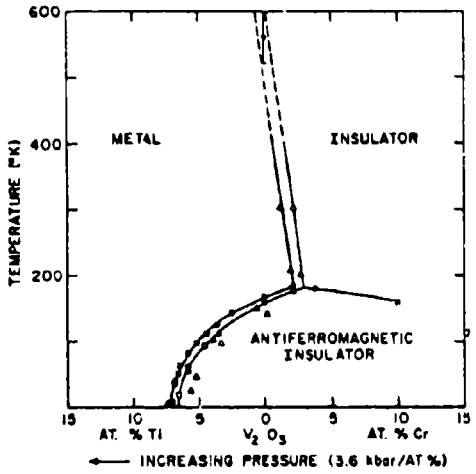
Rao et al.



Generalized phase diagram of transition temperature as a function of both pressure and at. % of chromium and titanium in V_2O_3

- ● mixed oxides at 1 atm.
- ■ □ V_2O_3 on increasing and decreasing pressures, resp.
- ▲ △ $(V_{0.96}Cr_{0.04})_2O_3$ for increasing and decreasing pressure

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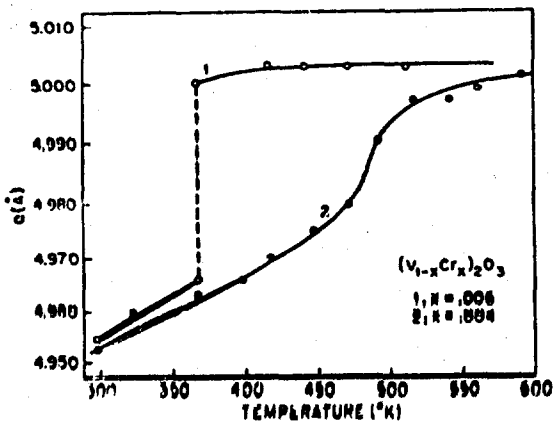
McWhan et al.



Lattice parameters as a function of temperature for two chromium-doped V_2O_3 crystals.

Jayaraman et al.

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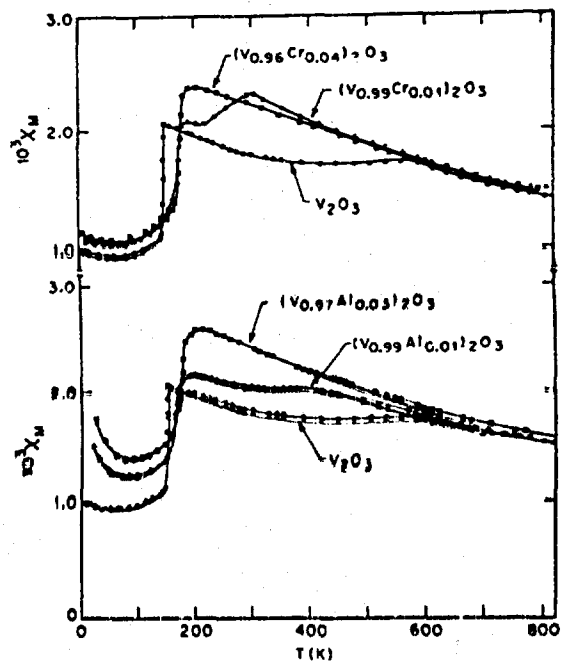

Magnetic susceptibility as a function of temperature for V_2O_3 and for chromium and aluminum containing V_2O_3 The undoped and chromium containing V_2O_3 were single crystals and the susceptibility was measured parallel to the c-axis. The aluminum containing samples are ceramic powder aggregates.

Gossard et al.

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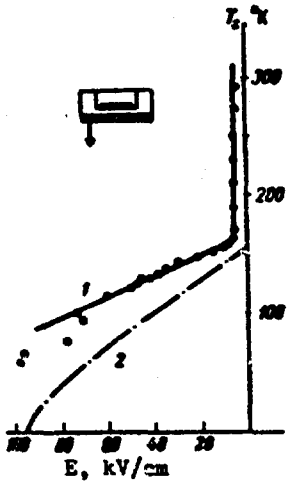

Transition temperature as a function of electrical field in sintered $(V_{0.91}Cr_{0.09})_2O_3$

The electrical field shifts the transition temperature similarly to the shift by hydrostatic pressure.

Andreev et al.

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INITIAL RATE OF CHANGE OF UPPER TRANSITION TEMPERATURE WITH COMPOSITION (dT_t/dx) FOR THE SUBSTITUTIONAL COMPOUNDS

$V_{1-x}M_xO_2$

[Critical compositions x_1 and x_2 indicate phase changes at 300°K. Room-temperature structures within the regions $x_1<x<x_2$ and $x>x_2$ are also indicated, where mono. refers to the monoclinic (P2/c) phase and ortho. to the orthorhombic (probable space group F222) phase.]

M	dT_t/dx (°K/at % M)	x_1	x_2	$x_1 < x < x_2$	$x > x_2$
Cr^{3+}	~+3	0.01	0.20	ortho.	(2φ)*
Fe^{3+}	+3	0.01	0.125	ortho.	two-phase
Ga^{3+}	+6.5	0.005	0.02	ortho.	two-phase
Al^{3+}	+9.0	0.005	0.045	ortho.	two-phase
Ti^{4+}	−0.5 to −0.7	0.2	0.2 to 0.25	ortho.	rutile and (2φ)*
Re^{4+}	~−4	0.07		rutile	
Ir^{4+}	~−4	0.04	0.5	rutile	two-phase
Os^{4+}	−7	0.03	0.1	rutile	two-phase
Ru^{4+}	−10	0.025	0.75	rutile	two-phase
Ge^{4+}	+5				
Nb^{5+}	−7.8	0.05	0.9	rutile	NbO_2
Ta^{5+}	−5 to −10	0.02	0.5	rutile	two-phase
Mo^{6+}	−5 to −10	0.03	0.55	rutile x = 1.0	(2φ)* mono.
W^{6+}	−28	0.013	0.68	rutile	ortho.
ordered trirutile phase about x = 0.33; 0.78 < x < 0.8 (2φ')* phase; 0.85 < x < 1 mono.					

* The 2φ phase is a distorted rutile structure with orthorhombic symmetry, and the 2φ' phase is similar but with monoclinic symmetry.

Goodenough and Pierce

BIBLIOGRAPHY

ADLER, D. Insulating and Metallic States in Transition Metal Oxides. SOLID STATE PHYSICS - ADVANCES IN RESEARCH AND APPLICATIONS, Edited by: SEITZ, F. et al. Volume 21, 1968. Academic Press, New York and London, p. 1-113.

ADLER, D. and J. FEINLEIB. Semiconductor-to-Metal Transition in V_2O_3. PHYS. REV. LETTERS, v. 12, no. 25, June 22, 1964. p. 700-703.

ALLERSMA, T. et al. Structure and Physical Properties of Solid and Liquid Vanadium Pentoxide. J. OF CHEM. PHYS., v. 46, no. 1, Jan. 1, 1967. p. 154-160.

ANDREEV, V.N. et al. Influence of a Strong Electric Field on the Temperature of the Dielectric-Metal Phase Transition in $(V_{0.91}Cr_{0.09})_2O_3$. JETP LETTERS, v. 13, no. 10, May 1971. p. 376-379.

ARIYA, S.M. and M.V. GOLOMOLZINA. Infrared Spectra of Titanium and Vanadium Oxides in the Crystalline State. SOVIET PHYS. SOLID STATE, v. 4, no. 10, Apr. 1963. p. 2142-2144.

ARNOLD, D.J. and R.W. MIRES. Magnetic Susceptibilities of Metallic V_2O_3 Single Crystals. J. OF CHEM. PHYS., v. 48, no. 5, Mar. 1, 1968. p. 2231-2234.

AUSTIN, I.G. The Effect of Pressure on the Metal-to-Insulator Transition in V_2O_3. PHIL. MAG., v. 7, no. 78, June 1962. p. 961-967.

AUSTIN, I.G. and N.F. MOTT. Metallic and Nonmetallic Behavior in Transition Metal Oxides. SCIENCE, v. 168, no. 3927, Apr. 1970. p. 71-77.

AUSTIN, I.G. and C.E. TURNER. The Nature of the Metallic State in V_2O_3 and Related Oxides. PHIL. MAG., v. 19, no. 161, May 1969. p. 939-949.

BACHMANN, H.G. et al. The Crystal Structure of Vanadium Pentoxide. ZEIT. FÜER KRISTALLOGRAPHIE, v. 115, no. 1/2, 1961. p. 110-131.

BANDO, Y. et al. Growth of VO_2 Single Crystals by Chemical Transport Reaction. JAPAN. J. OF APPL. PHYS., v. 8, no. 5, May 1969. p. 633-634.

BANUS, M.D. et al. Structural, Electrical, and Magnetic Properties of Vacancy-Stabilized Cubic TiO and VO. MASSACHUSETTS INST. OF TECHNOLOGY, Lincoln Lab. Solid State Research. May 15, 1969. p. 17-23.

BARKER, A.S., JR. et al. Infrared Optical Properties of Vanadium Dioxide Above and Below the Transition Temperature. PHYS. REV. LETTERS, v. 17, no. 26, Dec. 26, 1966. p. 1286-1289.

BARKER, A.S., JR. and J.P. REMEIKA. Optical Properties of V_2O_3 Doped with Chromium. SOLID STATE COMM., v. 8, no. 19, Oct. 1970. p. 1521-1524.

BERGLUND, C.N. and H.J. GUGGENHEIM. Electronic Properties of VO_2 Near the Semiconductor-Metal Transition. PHYS. REV., v. 185, no. 3, Sept. 15, 1969. p. 1022-1033.

BERGLUND, C.N. and A. JAYARAMAN. Hydrostatic-Pressure Dependence of the Electronic Properties of VO_2 Near the Semiconductor-Metal Transition Temperature. PHYS. REV., v. 185, no. 3, Sept. 15, 1969. p. 1034-1039.

BODÓ, Z. and I. HEVESI. Optical Absorption Near the Absorption Edge in V_2O_5 Single Crystals. PHYS. STATUS SOLIDI, v. 20, no. 1, 1967. p. K45-K49.

BOGDANOVA, N.I. and G.M. LOGINOV. Magnetic Susceptibility of Vanadium Oxide at 80 to 370°K. SOVIET PHYS. SOLID STATE, v. 4, no. 1, July 1962. p. 167-169.

BONGERS, P.F. Anisotropy of the Electrical Conductivity of Vanadium Dioxide Single Crystals. SOLID STATE COMM., v. 3, no. 9, Sept. 1965. p. 275-277.

BOYLE, W.S. and H.W. VERLEUR. Radiant Self-Stabilization of Temperature. APPLIED PHYS. LETTERS, v. 12, no. 2, Jan. 15, 1968. p. 28-31.

CARR, P.H. and S. FONER. Magnetic Transitions in Ti_2O_3 and V_2O_3. J. OF APPLIED PHYS., Supplement to v. 31, no. 5, May 1960. p. 344S-345S.

CHAMBERLAND, B.L. The Hydrothermal Synthesis of $V_2O_{4-x}F_x$ Derivatives. MAT. RES. BULL., v. 6, 1971. p. 425-432.

COOK, O.A. High Temperature Heat Contents of V_2O_3, V_2O_4 and V_2O_5. AMERICAN CHEM. SOC., J., v. 69, no. 2, Feb. 1947. p. 331-333.

COPE, R.G. and A.W. PENN. High-Speed Solid-State Thermal Switches Based on Vanadium Dioxide. BRITISH J. OF APPL. PHYS. (J. OF PHYS., D), v. 1, Ser. 2, 1968. p. 161-168.

DERBENWICK, G.F. Photoemission and Optical Studies of Strontium Titanate, TiO_2 and VO_2. STANFORD ELECTRONICS LABORATORY, Aug. 1970. AD 715 736.

DERNIER, P.D. and M. MAREZIO. Crystal Structure of the Low-Temperature Antiferromagnetic Phase of V_2O_3. PHYS. REV., B, Ser. 3, v. 2, no. 9, Nov. 1, 1970. p. 3771-3776.

DONNAY, J.D.H. (Editor). Crystal Data, Determinative Tables, 2nd Edition. AMERICAN CRYSTALLOGRAPHIC ASSOCIATION, Apr. 1, 1963. ACA Monograph no. 5.

EVERHART, C.R. and J.B. MacCHESNEY. Anisotropy in the Electrical Resistivity of Vanadium Dioxide Single Crystals. J. OF APPLIED PHYS., v. 39, no. 6, May 1968. p. 2872-2874.

FAN, J. and W. PAUL. Preparation and Properties of Thin Vanadium Oxide Films (In Fr.). LE VIDE, v. 25, no. 150, Nov./Dec. 1970. p. 232-243.

FEINLEIB, J. and W. PAUL. Semiconductor-to-Metal Transition in V_2O_3. PHYS. REV., v. 155, no. 3, Mar. 15, 1967. p. 841-850.

FILLINGHAM, P.J. Domain Structure and Twinning in Crystals of Vanadium Dioxide. J. OF APPLIED PHYS., v. 38, no. 12, Nov. 1967. p. 4823-4829.

FOËX, M. The Anomalous Electrical Properties of Vanadium Sesquioxide Between -100°C and +300°C (In Fr.). ACAD. DES SCI., C.R., v. 229, no. 18, Nov. 2, 1949. p. 880-882.

FULS, E.N. et al. Reactively Sputtered Vanadium Dioxide Thin Films. APPLIED PHYS. LETTERS, v. 10, no. 7, Apr. 1, 1967. p. 199-201.

GOODENOUGH, J.B. Band Structure of Transition Metals and Their Alloys. PHYS. REV., v. 120, no. 1, Oct. 1, 1960. p. 67-83.

GOODENOUGH, J.B. and J.W. PIERCE. Crystallographic Transitions in $V_{1-x}Cr_xO_2$ MASS. INST. TECH., LINCOLN LAB. QTR Feb. 1-Apr. 30, 1970. Con. F196-28-70-C-0230. p. 15-22. Aug. 1971.

GOODMAN, G. Electrical Conductivity Anomaly in Vanadium Sesquioxide. PHYS. REV. LETTERS, v. 9, no. 7, Oct. 1, 1962. p. 305.

GOSSARD, A.C. et al. Metal-Insulator Transitions of V_2O_3: Magnetic Susceptibility and Nuclear-Magnetic-Resonance Studies. PHYS. REV. B, v. 3, no. 12, June 15, 1971. p. 3993-4002.

GUNTERSDORFER, M. Conductivity Anomaly in Vanadium Dioxide (In Ger.). SOLID STATE ELECTRONICS, v. 13, no. 3, Mar. 1970. p. 355-367.

HANDBOOK OF CHEMISTRY AND PHYSICS, Cleveland, Ohio. The Chemical Rubber Company, 52nd Edition, 1971-1972.

HAZONY, Y. and H.K. PERKINS. Electronic Structure and Anomalous Thermal Expansion in FeF_2 and VO_2. J. OF APPLIED PHYS., v. 41, no. 13, Dec. 1970. p. 5130-5131.

HENSLER, D.H. Transport Properties of Sputtered Vanadium Dioxide Thin Films. J. OF APPLIED PHYS., v. 39, no. 5, Apr. 1968. p. 2354-2360.

HENSLER, D.H. et al. Reactively Sputtered Thin Films in the Vanadium-Oxygen System Using Triode Sputtering. ELECTROCHEM. SOC., J., v. 116, no. 6, June 1969. p. 887-889.

HEVESI, I. et al. Infrared Spectra of V_2O_5 Single Crystals. SOVIET PHYS., CRYSTALLOGRAPHY, v. 16, no. 2. Sept./71. p. 275-278

HEYWANG, W. and M. GUNTERSDORFER. Resistivity Temperature at Phase Transition in Vanadium Dioxide (In Ger.). HELV. PHYS. ACTA, v. 41, no. 6/7, 1968. p. 908-913.

HILL, G.J. and R.H. MARTIN. Electrical and Magnetic Properties of Vanadium Dioxide. PHYS. LETTERS, v. 27A, no. 1, May 20, 1968. p. 34-35.

HONIG, J.M. et al. Resistivity, Magnetoresistance, and Hall Effect Studies in Vanadium Monoxide. J. OF SOLID STATE CHEMISTRY, v. 2, no. 1, June 1970. p. 74-77.

HYLAND, G.J. On the Electronic Phase Transitions in the Lower Oxides of Vanadium. PHYS. SOC., PROC., (J. OF PHYS., C), v. 1, Ser. 2, no. 1, Feb. 1968. p. 189-207.

IOFFE, V.A. and I.B. PATRINA. Comparison of the Small-Polaron Theory with the Experimental Data of Current Transport in V_2O_5. PHYS. STATUS SOLIDI, v. 40, no. 1, July 1970. p. 389-395.

JACOBSEN, R.T. and M. KERKER. Optical Properties of Vanadium Pentoxide. OPTICAL SOC. OF AMERICA, J., v. 57, no. 6, June 1967. p. 751-755.

JAYARAMAN, A. et al. Critical Behavior of the Mott Transition in Cr-Doped V_2O_3. PHYS. REV. B, Ser. 3, v. 2, no. 9, Nov. 1, 1970. p. 3751-3756.

KABASHIMA, S. et al. High Frequency Conductivity of VO_2. PHYS. SOC. OF JAPAN, J., v. 22, no. 3, Mar. 1967. p. 932.

KACHI, S. et al. Electrical Conductivity of Vanadium Oxides. PHYS. SOC. OF JAPAN, J., v. 18, 1963. p. 1839-1840.

KAWAKUBO, T. and T. NAKAGAWA. Phase Transition in VO_2. PHYS. SOC. OF JAPAN, J., v. 19, no. 4, Apr. 1964. p. 517-519.

KAWANO, S. et al. Electric and Magnetic Properties of "VO". PHYS. SOC. OF JAPAN, J., v. 21, no. 12, Dec. 1966. p. 2744-2745. [A]

KAWANO, S. et al. Thermoelectric Power of Vanadium Monoxides. PHYS. SOC. OF JAPAN, J., v. 27, no. 4, Oct. 1969. p. 1076. [B]

KENNEDY, T.N. and F.M. COLLINS. A Vanadium Oxide Film-Switching Element. RENNSELAER POLYTECHNIC INSTITUTE, Technical Report No. 2. Feb. 1969. 27 p. AD 683 368.

KENNEDY, T.N. et al. Preparation and Properties of Crystalline and Amorphous Vanadium Pentoxide. MAT. RES. BULL., v. 2, no. 2, Feb. 1967. p. 193-201.

KENNY, N. et al. Optical Absorption Coefficients of Vanadium Pentoxide Single Crystals. J. OF PHYS. AND CHEM. OF SOLIDS, v. 27, no. 8, Aug. 1966. p. 1237-1246.

KHAN, F.Z. et al. Magnetic Susceptibility of V_2O_5. SOVIET PHYS. SEMICONDUCTORS, v. 2, no. 4, Oct. 1968. p. 377-381.

KIMIZUKA, N. et al. Crystal Growth of Vanadium Dioxide. MAT. RES. BULL., v. 5, no. 6, June 1970. p. 403-408.

KING, B.W. and L.L. SUBER. Some Properties of the Oxides of Vanadium and Their Compounds. AMERICAN CERAM. SOC., J., v. 38, no. 9, Oct. 1955. p. 306-311.

KIRCHNER, H.P. Thermal Expansion Anisotropy of Oxides and Oxide Solid Solutions. AMERICAN CERAM. SOC., J., v. 52, no. 7, July 1969. p. 379-386.

KIRIASHKINA, Z.I. et al. An Investigation of the Dielectric Permittivity of Semiconductors. SOVIET PHYS. TECH. PHYS., v. 2, no. 1, Jan. 1957. p. 69-73.

KITAHIRO, I. and A. WATANABE. Thermoelectric Power of Vanadium Dioxide Whisker. PHYS. SOC. OF JAPAN, J., v. 21, no. 11, Nov. 1966 p. 2423.

KITAHIRO, I. et al. Hall Effect of Vanadium Dioxide Powder. PHYS. SOC. OF JAPAN, J., v. 21, no. 11, Nov. 1966. p. 2422.

KOIDE, S. and M. TAKEI. Epitaxial Growth of VO_2 Single Crystals and their Anisotropic Properties in Electrical Resistivities. PHYS. SOC. OF JAPAN, J., v. 22, no. 3, Mar. 1967. p. 946-947.

KOSUGE, K. The Phase Transition in VO_2. PHYS. SOC. OF JAPAN, J., v. 22, no. 2, Feb. 1967. p. 551-557. [A]

KOSUGE, K. The Phase Diagram and Phase Transition of the V_2O_3-V_2O_5 System. J. OF PHYS. AND CHEM. OF SOLIDS, v. 28, no. 8, Aug. 1967. p. 1613-1621. [B]

KOSUGE, K. et al. Phase Diagram and Magnetism of V_2O_3-V_2O_5 System. PHYS. SOC. OF JAPAN, J., v. 18, 1963. p. 318-319. [A]

KOSUGE, K. et al. Phase Transition in V_6O_{13}. PHYS. SOC. OF JAPAN, J., v. 20, no. 1, Jan. 1965. p. 178-179. [B]

LADD, L.A. and W. PAUL. Optical and Transport Properties of High Quality Crystals of V_2O_4 Near the Metallic Transition Temperature. SOLID STATE COMM., v. 7, no. 4, Feb. 1969. p. 425-428.

MacCHESNEY, J.B. and H.J. GUGGENHEIM. Growth and Electrical Properties of Vanadium Dioxide Single Crystals Containing Selected Impurity Ions. J. OF PHYS. AND CHEM. OF SOLIDS, v. 30, no. 2, Feb. 1969. p. 225-234.

MacCHESNEY, J.B. et al. Preparation and Properties of Vanadium Dioxide Films. ELECTROCHEM. SOC., J., v. 115, no. 1, Jan. 1968. p. 52-55.

McCULLOCH, J.C. Electrical Properties of Vanadium Pentoxide. OREGON STATE UNIV., Corvallis. Contract NONR-1286(08). May 27, 1968. 53 p. AD 670 560.

MacKENZIE, J.D. Preparation of Properties of Non-Crystalline Films. RENSSELAER POLYTECHNIC INST., Troy, New York. Contract N00014-67-A-0117. Mar. 1969. AD 687 123.

MacMILLAN, A.J. Electric and Magnetic Properties of V_2O_3 and Related Sesquioxides. MASSACHUSETTS INST. OF TECHNOLOGY. Contract AF 19-604-5482 and Nonr 1841-10. Oct. 1962. AD 291 459.

McWHAN, D.B. et al. Mott Transition in Chromium doped V_2O_3. PHYS. REV. LETTERS, v. 23, no. 24, Dec. 1969. p. 1384-1387.

McWHAN, D.B. and T.M. RICE. Critical Pressure for the Metal-Semiconductor Transition in V_2O_3. PHYS. REV. LETTERS, v. 22, no. 17, Apr. 28, 1969. p. 887-890.

MASSARD, P. et al. Study of the Vanadium Oxide System with Over 50% Vanadium (In Fr.). ANN. DE CHIM., v. 4, no. 3, May-July 1969. p. 147-151.

MINOMURA, S. and H.G. DRICKAMER. Effect of Pressure on the Electrical Resistance of Some Transition-Metal Oxides and Sulfides. J. OF APPLIED PHYS., v. 34, no. 10, Oct. 1963. p. 3043-3048.

MINOMURA, S. and H. NAGASAKI. The Effect of Pressure on the Metal-to-Insulator Transition in V_2O_4 and V_2O_3. PHYS. SOC. OF JAPAN, J., v. 19, no. 1, Jan. 1964. p. 131-132.

MOKEROV, V.G. and A.V. RAKOV. Optical Properties and Band Structure of Vanadium Dioxide and Pentoxide Single Crystals. SOVIET PHYS. SOLID STATE, v. 11, no. 1, July 1969. p. 150-152.

MORIN, F.J. Oxides Which Show a Metal-to-Insulator Transition at the Neel Temperature. PHYS. REV. LETTERS, v. 3, no. 1, July 1, 1959. p. 34-36.

NAGASAWA, K. et al. Growth of V_5O_9 Single Crystals. JAPAN. J. OF APPL. PHYS., v. 9, no. 4, Apr. 1970. p. 407. [A]

NAGASAWA, K. et al. Growth of V_3O_5 and V_6O_{11} Single Crystals. JAPAN. J. OF APPL. PHYS., v. 8, no. 10, Oct. 1969. p. 1267. [B]

NAKAHIRA, M. et al. Low-Temperature Phase Transition of Vanadium Sesquioxide. J. OF APPLIED PHYS., v. 41, no. 2, Feb. 1970. p. 836-838.

NEUMAN, C.H. et al. Pressure Dependence of the Resistance of VO_2. J. OF CHEM. PHYS., v. 41, no. 6, Sept. 1964. p. 1591-1595.

NEWNHAM, R.E. and Y.M. De HAAN. Refinement of the alpha Al_2O_3, Ti_2O_3, V_2O_3 and Cr_2O_3 Structures. ZEIT. FUER KRISTALLOGRAPHIE, v. 117, no. 2/3, 1962. p. 235-237.

OKINAKA, H. et al. Electrical Properties of the V_3O_5 Single Crystals. PHYS. SOC. OF JAPAN, J., v. 27, no. 5, Nov. 1969. p. 1366-1367. [A]

OKINAKA, H. et al. Electrical Properties of V_8O_{15} Single Crystal. PHYS. LETTERS, v. 33A, no. 6, Nov. 30, 1970. p. 370-371. [B]

OKINAKA, H. et al. Electrical Properties of V_6O_{11} and V_7O_{13} Single Crystals. PHYS. SOC. OF JAPAN, J., v. 29, no. 1, Jan. 1970. p. 245-246. [C]

OKINAKA, H. et al. Electrical Properties of the V_5O_9 Single Crystals. PHYS. SOC. OF JAPAN, J., v. 28, no. 3, Mar. 1970. p. 803. [D]

OKINAKA, H. et al. Electrical Properties of the V_4O_7 Single Crystals. PHYS. SOC. OF JAPAN, J., v. 28, no. 3, Mar. 1970. p. 798-799. [E]

PATRINA, I.B. and V.A. IOFFE. Electrical Properties of Vanadium Pentoxide. SOVIET PHYS. SOLID STATE, v. 6, no. 11, May 1965. p. 2581-2585.

POWELL, R.J. et al. Photoemission from VO_2. PHYS. REV., v. 178, no. 3, Feb. 15, 1969. p. 1410-1415.

RAO, C.N.R. et al. Phase Transitions and Conductivity Anomalies in Solid Solutions of VO_2 with TiO_2, NbO_2 and MoO_2. J. OF PHYS. AND CHEM. OF SOLIDS, v. 32, no. 6, 1971. p. 1147-1150.

RICE, T.M. and D.B. McWHAN. Metal-Insulator Transition in Transition Metal Oxides. IBM J. OF RES. AND DEVELOPMENT, v. 14, no. 3, May 1970. p. 251-257.

ROACH, W.R. and I. BALBERG. Optical Induction and Detection of Fast Phase Transition in VO_2. SOLID STATE COMM., v. 9, no. 9, Sept. 1971. p. 551-555.

ROCH, J. Measurement of Susceptibility of Vanadyl Sulfate and its Thermal Decomposition Products. ACAD. DES SCI., C.R., v. 249, no. 1, July 1959. p. 56-58.

ROZGONYI, G.A. and D.H. HENSLER. Structural and Electrical Properties of Vanadium Dioxide Thin Films. J. OF VACUUM SCI. AND TECHNOLOGY, v. 5, no. 6, Nov./Dec. 1968. p. 194-199.

ROZGONYI, G.A. and W.J. POLITO. Preparation of Thin Films of Vanadium (Di-, Sesqui-, and Pent-) Oxide. ELECTROCHEM. SOC., J., v. 115, no. 1, Jan. 1968. p. 56-57.

SAMOKHVALOV, A.A. Ultra-High Frequency Dielectric Properties of a Group of Oxides of 3d Transition Metals. SOVIET PHYS. SOLID STATE, v. 3, no. 12, June 1962. p. 2613-2618.

SCHMIDT, B. Technology of Vanadium Thermistors (in Polish). ARCHIWUM ELEKTROTECHNIKI, v. 18, no. 2, 1969. p. 405-411.

SHTORCH, P. and Y. YACOBY. Optical Thermoreflectance in V_2O_3. PHYS. LETTERS, v. 36A, no. 2, Aug. 16, 1971. p. 89-90.

SINCLAIR, W.R. et al. Materials for Use in a Durable Selectively Semitransparent Photomask. ELECTROCHEM. SOC., J., v. 118, no. 2, Feb. 1971. p. 341-344.

STRINGER, J. The Vanadium-Oxygen System-A Review. J. OF LESS-COMMON METALS, v. 8, no. 1, Jan. 1965. p. 1-14.

TAKEI, H. and S. KOIDE. Epitaxial Growth of VO Single Crystals and their Electrical Properties. PHYS. SOC. OF JAPAN, J., v. 24, no. 6, June 1968. p. 1394. [A]

TAKEI, H. and S. KOIDE. Growth and Electrical Properties of Vanadium-Oxide Single Crystals by Oxychrolide Decomposition Method. PHYS. SOC. OF JAPAN, J., v. 21, no. 5, May 1966. p. 1010. [B]

TOULOUKIAN, Y.S. (Editor) Thermophysical Properties of High Temperature Solid Materials. Thermophysical Properties Research Center. New York, McMillan, 1967, volume 4, part 1.

TOURKY, A.R. et al. The Color Problem of Vanadium Pentoxide. II. Temperature Dependence of Magnetic Suscentibility of Vanadium Pentoxide. Z. FUER PHYSIK. CHEM. (LEIPZIG), v. 230, no. 3/4, 1965. p. 184-188.

VALIEV, K.A. et al. Optical and Electrical Parameters of Vanadium Dioxide in a Strong Electrical Field. SOVIET PHYS. SOLID STATE, v. 13, no. 2, Aug. 1971. p. 342-343.

VAN STEENSEL, K. et al. Thin-Film Switching Elements of VO_2. PHILIPS RES. REPTS., v. 22, 1967. p. 170-177.

VERLEUR, H.W. et al. Optical Properties of VO_2 Between 0.25 and 5 eV. PHYS. REV., v. 172, no. 3, Aug. 15, 1968. p. 788-798.

VOLZHENSKII, D.S. and M.V. PASHKOVSKII. Conduction Mechanism in Vanadium Pentoxide. SOVIET PHYS. SOLID STATE, v. 11, no. 5, Nov. 1969. p. 950-953.

WALDEN, R.H. Two Switching Devices Utilizing VO_2. IEEE TRANS. ON ELECTRON DEVICES, v. ED-17, no. 8, Aug. 1970. p. 603-612.

WARREN, W.W., JR. et al. Nuclear Magnetic Resonance and Relaxation in VO. AMERICAN PHYS. SOC., BULL., v. 12, Ser. 2, Dec. 1967. p. 1117.

WESTMAN, S. Note on a Phase Transition in VO_2. ACTA CHEM. SCAND., v. 15, 1961. p. 217.

ZHUZE, V.P. et al. The Hall Effect in V_2O_3 Single Crystals in the Metallic Conductivity Region. SOVIET PHYS. SOLID STATE, v. 10, no. 12, June 1969. p. 2914-2916. [A]

ZHUZE, V.P. et al. Reflectivity of the Metallic Phase of V_2O_3. SOVIET PHYS. SOLID STATE, v. 13, no. 1, July 1971. p. 260-261. [B]