NBS

Technical Note 153

A GENERAL SURVEY OF THE SEMICONDUCTOR FIELD

GEORGE WILLIAM REIMHERR

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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AUGUST 1962

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A GENERAL SURVEY OF THE SEMICONDUCTOR FIELD

by

George William Reimherr

ABSTRACT

This survey presents a listing of some of the properties and applications of a number of single-element and binary compound inorganic semiconductors. Brief mention is made of other types of semiconductors (ternary compounds, mixed crystals, alloys, ferrites, and organics). The toxicity problem presented by many semiconductors is noted.

SECTION I

INTRODUCTION

Electronics has become a semiconductor-oriented industry. This situation has come about logically, because semiconductors appear to offer a large reduction in size and power, as well as a potential for increased reliability over previous methods. Many new semiconductor devices have come into being within the last decade.

The computer industry promises to be one of the major potential markets for semiconductors. The drive to increase the speed, reliability, and applications of modern digital computers has naturally focused increased attention on semiconductor devices. Actual or potential uses for semiconductors include such things as circuit elements (resistors, capacitors, diodes, transistors, etc.), storage elements (tunnel diodes, delay lines, electroluminescent cell-photoconductive cell combinations, etc.), power sources (solar cells, thermoelectric generators), various measuring devices (germanium thermometers, Hall effect ammeters, etc.), thermoelectric cooling devices, and others.

Present-day semiconductor devices are still dominated by the two giants of the semiconductor field -- silicon and germanium. These two enjoy an advantage over all other semiconductors in that their technology is comparatively well advanced, resulting in a high degree of crystal perfection. While silicon and germanium do possess good physical and electrical properties, their properties are not necessarily the ultimate for a given practical application. As a result, there is increasing competition from other semiconductors, one or more of which may someday rival silicon and germanium in overall importance. The present survey represents an attempt to list some of the properties and applications of present-day semiconductors. It runs the gamut from relatively unimportant semiconductors to those that are extremely important. The survey certainly does not exhaust the field of possible semiconductors. Some are not important enough as semiconductors to merit mention. Many other semiconductors are still experimentally unconfirmed in the laboratory. The number of usable semiconductors is further reduced by the occurrence of phase changes or low melting points.

The survey includes the 12 single-element semiconductors known to exist and also the most important binary compound inorganic semiconductors. Brief mention is given to the other types -- the ternary compounds, the mixed crystals, the alloys, the ferrites, and the organics. Also included are a few comments concerning the crystal structures of the semiconductors and the toxicity problem presented by many of the inorganic compound semiconductors.

SECTION II

SINGLE ELEMENT AND BINARY COMPOUND SEMICONDUCTORS

This section, by far the biggest part of this survey consists mostly of the data of Table I.

The Key to Table I

The following items represent the various physical properties and applications of the semiconductors listed in Table I. These items are given in the same order as the column headings in Table I.

1. Semiconductors. This is a listing of the most important single element and binary compound semiconductors mentioned in the recent literature (1957 - 1961).

2. Eg. This represents the width of the energy gap of the semiconductor in electron volts (e.v.). The superscript r, given beside the reference number, refers to the value at room temperature, whereas the superscript* refers to the value extrapolated to 0°K. The absence of a superscript indicates that the reference temperature is not known to the author.

3. ε This is the dielectric constant of the semiconductor. For example, germanium has a dielectric constant of 16.

4. u_n, u_p. These represent the quoted values for electron mobility (u_n) and hole mobility (u_p), respectively, in units of cm^2/volt-sec., and at room temperature.

5. Crystal Structure. This represents the ordered arrangement of the atoms in the crystal lattice. "Strukturbericht" symbols are used (see Table II). In particular, B1 refers to the rock salt structure, B3 to the zinc blende structure, and B4 to the wurtzite structure.

6. Physical Appearance. This indicates how the semiconductor might look to an observer.

7. Known Number of Research Groups. This indicates the number of different research groups, domestic or foreign, submitting papers recently concerning that particular semiconductor. The sampling of papers included thousands of articles (53) and therefore serves as an indication of the relative importance of, or interest in, that semiconductor. For example, the sampling indicated that 82 research groups submitted at least one research paper each on germanium, whereas only 6 different research groups submitted papers concerning AlSb. The absence of a

number in this column indicates that the sampling of articles taken for that particular semiconductor was too small to make any number meaningful in the relative sense mentioned above.

8. Thin Film. An X in this column indicates that the material has reportedly been prepared as a thin film.

9. Electronic Applications. This is a listing of the various electronic applications for which the particular semiconductor has been considered. An attempt was made to separate those applications that have resulted in commercial devices from those applications still only under study in the research laboratory. It is quite possible that a device listed under lab study may since have become commercially available.

10. Comments. This is a group of miscellaneous comments that for one reason or another did not properly fit into one of the other columns, but did still merit brief mention.

11. References. The references are listed in parentheses. See Selected Bibliography at the end of the report.

OTHER ABBREVIATIONS

1.	A	Angstrom units
2.	atm.	atmosphere
3.	b. c.	body centered
4.	cc.	cubic centimeters
5.	cm.	centimeters
6.	cr.	crystalline
7.	hex.	hexagonal
8.	monocl.	monoclinic
9.	orthor.	orthorhombic
10.	rhomb.	rhombohedral (hex. system)
11.	sec.	second
12.	temp.	temperature
13.	tetr.	tetragonal
14.	thermoel.	thermoelectric
15.	$\sim$	about, approximately

Table 1. A Listing of Various Single Element and Binary Compound Semiconductors, Along with Some of Their Physical Properties and Applications

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
1. AgI	2.8 $(1)^r$ (2)	-	3 (2)	-	B3 and B4 (3)	pale yellow powder, darkening on exposure to light (4)	1	-	-	-	AgI is used in medicine,photography, and artificial rainmaking attempts (4).
2. Ag_2S	see comments	-	-	-	cubic, b.c. (5)	grayish-black, heavy powder (4)	0	-	-	photoconductive and photovoltaic cells (3)	Ag_2S is a semiconductor below 177°C, but at higher temperatures it tends to have metallic conduction properties. It is noted for its large ionic conductivity in its low temperature form (3). In 1833, Faraday made probably the first significant observation in the field of semiconductivity when he found that silver sulfide has a negative temperature coefficient of resistance(6) Silver sulfide becomes metallic at 65,000 atm, pressure (7).
3. Ag_2Se	0.075 (8)	-	2,000 (8)		cubic above 133°C (9); orthor. at room temp. (8)	thin gray plates (5)	1	-	-	thermoel. studies	The phase change occurring during cooling of the material from the melt makes it difficult to prepare large single crystals (9). Metallic behavior is noted above the transition temp. of 133°C (8).
4. Ag_2Te	0.17 $(1)^r$ 0.02 (10)	-	-	-	cubic above 130°C; orthor. below that (10)	gray (5)	1	-	-	thermoel. cooling	Phase changes at 130°C cause difficulties in the growth of single crystals (10). While apparently not competitive with Bi_2Te_3 for room-temperature cooling applications, Ag_2Te_3 might prove useful at lower temperatures in its extrinsic conductivity range (10).

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
5. AlAs	2.16 (12)^r ~2.2 (11)^r	-	1200 (13)	200 (13)	B3 (14)	solid; highly toxic (15)	0	-	-	-	Both AlAS and AlP are quite unstable when exposed to a moist atmosphere (2). They hydolyze slowly under atmospheric conditions, evolving AsH_3 and PH_3 **(16)**. Few electrical measurements appear to have been made on either AlAS or AlP(2).
6. AlB	large (6998)	-	-	-	-	-	1	-	-	possible use at high temperatures.	AlB is a very hard material, following directly behind diamond and boron carbide in the scale of hardness (5).
7. AlN	-	-	-	-	B4 **(17)**	clear white cr. (5)	3	-	-	electro-luminescence studies (4254)	
8. Al_2O_3	2.5 (18) ~7 (16)	see comments	-	-	$D5_1$ (18)	colorless (5)	-	X	-insulator for vacuum tube heater elements -dielectric in electrolytic capacitors	-thin film majority carrier amplifier -masers	Aluminum oxide is one of the best over-all dielectric materials available. When formed on high purity aluminum foil, it has a dielectric constant of from 7 to 10, and a dielectric strength of 2.5 million volts per 0.1 inch of thickness **(19)**.
9. AlP	2.42 (7589)^r 3.1 (12)^r (13)	11.6 (13)	3500 (13)	-	B3		2	-	-	-	See comments for AlAs.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μn	μp					COMMERCIAL DEVICES	LAB STUDY	
10. AlSb	1.52 (11)^r 1.6 (2)* (12)^r	8.4 (3) 10.1 (13) (16)	35 (3) 50 (11) 400 (2) 200 (13)	150 (3) (2) 200 (20) > 400 (6362)	B3 (14)	-	6	-		-rectifier for high temp. applications. -photovoltaic cell. -infra-red optics. (21) -transistors	AlSb in particular, but all the antimonides to some degree show sensitivity of surface properties to exposure to air(3). AlSb decomposes in a moist atmosphere (11). AlSb has about the same theoretical conversion efficiency as a photovoltaic device as has GaAs (22).
11. As	~1.2 (2)*	-	~65 (2)	~ 65 (2)	see comments	gray powder (see comments)	-	X	-	-	Arsenic is a metal in its usual form. However, when evaporated as a thin film, it is amorphous and this gray arsenic shows some semiconducting properties. (3)
12. As_2Se_3	1.6 (2)^r	-	-	-	-	amorphous or glassy (16)	-	-	-	-	-
13. As_2Te_3	1.0 (2)^r (18)	-	170 (18) (2)	80 (2)	monocl. (16) (18)	-	0	-	-	-	As_2Te_3 has a low melting point, 362°C, and a fairly large energy gap. Since it is easily liquified, it may prove useful to study the effect of lattice order on the electrical properties of semi-conductors. (9)

SEMI-CONDUCTORS	E_g (ev)	ϵ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
14. B	~1 (3) 1.1 (20) 1.6 (11)^{r} ~1.7 (2)*	6.2 (20)	~1 (2)	~1 (2)	complex (3) complex tetr. (2)	very soft, brown, amorphous powder or as crystals; ignites in air (4)	6	X	-	-	Boron is one of the least understood semiconductors. It is also one of the most difficult to work with (3). It, like diamond, has purely valence bonds (20). It has exceptionally low carrier mobilities, with hole mobility being slightly greater than electron mobility (2).
15. BAs	-	-	-	-	B3 (2035)	-	1		-	-	-
16. BN	4.6 (16) (20) -about twice that of diamond (6066)	-	-	-	B3 (6066)	white (5)	2	-	-	-	BN in its cubic form is an extremely hard material. It may eventually prove useful for semiconductor applications in extreme environments.
17. BP	5.9 (4552) ~6 (13)	11.6 (13)	-	100 (13) ~300 (4552)	B3 (2035)	maroon powder (5)	3	-	-	-	-
1B. BaO	≥3.B (16)	34 (16)	small; ~3 at 500°K (16)	-	B1 (1B)	colorless (16)	-	-	oxide cathodes	-	BaO reacts rapidly with moisture in the air (16). Little is known concerning the semiconducting properties of two other alkaline earth oxides, CaO and SrO (16) The fourth member of the group, MgO, has received some attention as a semiconductor.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
19. BiI_3	-	-	-	-	hex. (5)	grayish-black, metallic, glistening crystals. (4)	0	-	-	-	BiI_3 is mentioned here only as an example of one of the group VB tri-iodides that are known to be semi-conducting **(14)**.
20. Bi_2S_3	1.3 $(2)^r$ **$(16)^r$**	-	-	-	orthor. **(16)**	blackish-brown powder (4)	-	X	-	-	-
21. BiSe	-	-	-	-	-	-	0	-	-	-	Most semiconductors can conveniently be written as normal ionic compounds - (e.g., $Cd^{+2} + S^{-2} \longrightarrow CdS$). BiSe is mentioned merely as an example of an exception to this rule. **(18)** Otherwise, no exceptional importance was noted for BiSe.
22. Bi_2Se_3	0.3 $(2)^r$ 0.35 **$(16)^r$** **(18)**	-	600 **(18)** (2) **1600** **(8268)**	-	C33 **(18)** (9)	black (5)	1	-	-	thermoelectric study	Bi_2Se_3 - Bi_2Te_3 alloys have been investigated for thermoelectric applications **(23)**.
23. Bi_2Te_3	0.15 **(18)** 0.16 **(21)** 0.2 (2)*	-	800 **(18)** 1200 (2)	400 (2)	C33 **(18)**	gray hexagonal platelets (4)	16	-	-	thermoelectric	The electrical properties of Bi_2Te_3 show a high degree of anisotropy (2) Bi_2Te_3 is the most intensively studied of all the thermoelectric materials. It has been used as a Peltier cooling material since 1954 **(23)**. It is an attractive thermoelectric material partly because of its low thermal conductivity (11). Other compounds have been developed by substituting either Sb for part of the Bi, or Se for part of the Te **(23)**.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
24. C (diamond)	5.3 (2)^r **(20)** 5.6 (11)^r	5.7 **(20)** (586)	1800 (1) (2) (11)	1200 (1) (11) 1300 (2)	diamond	semi-conducting diamonds prepared with boron impurity are blue **(23)** hardest substance known (4)	16	-	-	**- Thermistors (8457)** **-Possible use at high temperatures and/or under severe ambient conditions.**	Semiconducting diamonds are rare in nature, accounting for less than one percent of natural diamonds. Only p-type semiconducting diamonds have successfully been grown in the laboratory **(23).** Semiconducting diamonds are designated as type IIb; type II diamonds do not have absorption bands between 6 and 13 microns, whereas type I diamonds do have absorption bands in this wavelength region (3724). Type IIb diamonds, in addition, have moderate conductivity at ordinary temperatures (2377). One sample reportedly had a resistivity of 270 Ω-cm at 20°C **(16).**
25. C (graphite)	-	-	-	-	hex., also rhomb. (less common) **(24)**	black, metallic like substance with a greasy feel (3)	11	-	-	-windows for soft x-rays -carbon element cryogenic temp.probe **(23)**	Graphite is the stable form of carbon at room temperature (3). Its conductivity is highly anisotropic. The conductivity along the plane of the crystals has been found to be on the order of 100 times greater than that normal to the planes (3). It is in this direction normal to the planes that graphite shows semiconductor properties, whereas its properties are more metallic along the planes **(20).**
26. Ca_2Pb	0.46 (1)^r **(16)** *	-	-	-	tetr. **(16)**	-	0	-	-	-	It is necessary to handle Ca_2Pb, Ca_2Si, and Ca_2Sn under an inert atmosphere in order to prevent their decomposition **(16)**

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			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
27. Ca_2Si	0.9 $(1)^r$ 1.9 $(11)^r$ **(16)***	-	-	-	tetr. **(16)**	-	0	-	-	-	See comments for Ca_2Pb.
28. Ca_2Sn	0.9 $(1)^r$ **(16)** *	-	-	-	tetr. **(16)**	-	0	-	-	-	See comments for Ca_2Pb.
29. $CdAs_2$	1.00, E∥C; 1.04, E⊥C $\mathbf{(25)}^r$ 1.1 (2)*	-	>300 (2) 100, a-axis; 400, c-axis **(25)**	no p-type reported **(25)**	tetr. **(25)**	-	1	-	-	-	Both the electrical and the optical properties of $CdAs_2$ show marked anisotropy **(25)** The conductivity was found to be four times greater in the c-direction (crystallographic) than in the a-direction (4281).
30. Cd_3As_2	0.13 $\mathbf{(25)}^r$ $(7027)^r$ 0.5 (2)*	-	10,000 (2) 15,000 **(25)** (7027)	no p-type reported **(25)**	$D5_9$ (9) **(18)**	dark gray (5)	2	X	-	-	Cd_3As_2 is remarkable in that it has a high value of electron mobility at room temperature ($u_n \sim 10{,}000$ cm^2/volt-sec.) at high levels of conduction electron density ($\sim 10^{18}$/cc) (4612). The other high electron mobility compounds (InSb, InAs, HgSe, and HgTe) all have the zinc blende structure.
31. CdI_2	-	-	-	-	C6 **(18)**	white, flaky crystals, becoming yellow when exposed to light and air (4)	0	-	-	-	CdI_2 is used in photography, medicine, etc. (4).

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32. CdO	2.3 (2)^r ~2 (8422)	-	20 (2)	-	B1 (2) (18)	yellowish-red, or brownish-red to brownish-black powder (4)	-	X	-	-	CdO was used in some of the earlier studies on semiconductors (2).
33. CdS	2.4 (2)* 2.42 (1)^r	11.6 (20) 5.4 (13)	210 (2) (18) 295 (13)	-	B3 and B4 (3)	light yellow or orange powder (4)	37	X	-photoconductive cells - γ-ray detector -scintillation counters (4) -phosphors	-thin film majority carrier amplifier -solar cells -photorectifier -phototransistor	CdS is one of the most sensitive materials for the detection of visible light (via photoconductivity) (20). Photoconductive cells made from it have spectral peaks from 5100 A to 6500 A (26). CdS crystals are strongly piezoelectric (23). CdS is an excellent detector for short wavelength radiation.
34. CdSb	0.46 (25)^r 0.48 (9) 0.57 (11,436)* 0.51 (4281)	-	250 (2)	300-700 (2) 900-1200 (25)	orthor. (5)	-	4	-	-	thermoelectric devices	CdSb has anion - anion bonds. The anions are linked in pairs (14).
35. CdSe	1.74 (1)^r (18) 1.85 (2)*	-	100 (2) 700 (18) 500 (13)	-	B4 (5) (9) B3 (18)	usually a red powder, but may also occur gray to brown (4)	5	X	photoconductive cells	-	Photoconductive cells made of CdSe peak in the range from 7000 A to 8000 A (26).

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			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
36. CdTe	1.4 (18) 1.45 $(1)^r$ 1.6 (2)*	~11 (13)	300 (18) 950 (2) 800 (13)	90 (2) 100 (13)	B3 (18)	brownish-black, cubic crystals (4)	8	X	-	-photoconductive and photovoltaic cells -infra-red detection -high temp. rectifiers and transistors	CdTe oxidizes on prolonged exposure to moist air (4).
37. $CoSb_3$	-	-	-	-	-	-	1	-	-	thermoelectric applications (20)	-
38. CsAu	probably between 2.6 and 3.3 (4284)	-	-	-	cubic, CsCl type (4284)	-	1	-	-	-	-
39. Cs_3Sb	1.6 (27)	-	-	~10 (27)	cubic (28)	-	1	X	-	-photocathodes- -photovoltaic effects in Cs_3 Sb films noted (11,459)-	-Cs_3Sb is useful because of its photo-emissive properties. -In spite of its wide band gap, Cs_3Sb has a relatively high room temperature conductivity- about $10^{-2}\Omega^{-1}cm^{-1}$. This is probably because of a departure from stoichiometry (27).

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			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
40. Cu_2O	2.0 (2)* 2.1 $(1)^r$	8.75 (20)	see comments	60 - 80 (20) 100 (2)	C3 (18)	reddish-brown cr. powder (4)	7	-	rectifiers	-electro-luminescence studies -photovoltaic cells	-Cu_2O is always p-type (29). -Cu_2O was probably the first semi-conductor in which intrinsic conductivity was recognized (3). -Cu_2O has been used as a rectifier material for a long time.
41. Fe_2O_3	2.3 (18)	-	-	-	$D5_1$ (18)	dense, dark-red powder (4)	-	-	-	thermoelectric generator (30)	Mobility values of about 100 cm^2/volt-sec. have been observed above the Curie point in the oxides Fe_2O_3 and Fe_3O_4 (2). Fe_2O_3 shows a weak ferromagnetism (16).
42. FeS_2 (pyrites)	-	-	-	-	C2 (5) (18)	brass-yellow or brown tarnished mineral, metallic luster (4)	0	-	-	-	Pyrites are very widely distributed, being the most common sulfide mineral (4). Pyrites have historical significance. It was one of the first materials found to show rectifying properties when used with metal contacts (6).

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43. GaAs	1.35 (11)^r (31)^r (32)^r 1.6 (2)*	11.1 (16) (22) (13)	4000 (11) (31) 5000 (22) 6700 (6356) 7500 (13) 8600 (23)	400 (2) (22) 450 (31) (6357)	B3 (9)	-	23	X	-varactor diodes -tunnel diodes -backward diodes	-solar cells -switching transistors -infra-red optics -ultrasonic delay lines	-Most of the GaAs produced by routine production methods is n-type, with a carrier concentration between 10^{16} and 10^{17} per cc, and having a resistivity below one ohm-cm. (33). The present problem with GaAs is that of getting the material with sufficient purity for reasonable carrier lifetimes. As a result, its present uses are limited to devices not requiring long lifetimes (23) - e.g., fast switching computer diodes. -Theoretically, GaAs transistors could have the excellent high-frequency characteristics of germanium transistors, in combination with a power handling capability exceeding that of silicon transistors (34). -GaAs is one of the most useful piezoresistive materials, along with silicon and germanium (35). -GaAs is close to the optimum material for photovoltaic solar energy conversion for temperature below 200°C (6519). Conversion efficiency as high as 13% has been achieved (22). In addition, GaAs solar cells have relatively high radiation damage resistance (22).
44. GaP	2.20 (4679)^r 2.25 (1)^r (11)^r 2.4 (2)*	~8.4 (16) 8.8 (13)	80 (13)	20 (2) 100 (13)	B3 (14)	pale orange, transparent crystals or whiskers (4)	10	X	-	-power rectifiers -transistors -high temp. diodes -electroluminescence studies	GaP has exhibited electroluminescence under a rectifying point contact (16).

SEMI-CONDUCTORS	E_g (ev)	ϵ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
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45. GaSb	0.68 **(36)** 0.70 **(32)** ^{r} 0.78 (1) ^{r} 0.8 (2)* (3)	14.0 (3) **(16)** **(22)**	4000 **(22)** 5000 (2) (11) **(20)**	850 **(22)** 1000 (2) (3) (11)	B3 (9)	-	8	-	tunnel diodes	-rectifiers -transistors	GaSb looks and handles like germanium; chemically, it is a little more reactive than is germanium **(22)**.
46. GaSe	1.97 **(37)** ^{r}	-	-	15 **(37)**	-	dark red-brown, greasy leaf (5)	1	-	-	photoconductivity	-The properties of GaSe crystals are very similar to those of ZnTe crystals in many ways **(37)**.
47. Ga_2Se_3	1.88 **(37)** ^{r}	-	-	-	B3 **(18)**	reddish-black; hard, brittle (5)	1	-	-	-	-
48. Ga_2Te_3	1.8 (3429)*	-	-	-	B3 **(18)**	black; hard, brittle cr. (5)	1	-	-	-	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
49. Ge	0.66 (38)^r 0.67 (31)^r (32)^r 0.75 (3)* 0.785 (2)*	16.0 (22) (29)	3800 (1) (3) (22) 3900 (31) (38) (13)	1800 (1) 1900 (22) (31) (38)	diamond	bright silvery, metallic luster (3)	82	X	-diodes (ordinary) -tunnel diodes -varactor diodes -transistors -photodiodes -phototransistors -infra-red detectors -infra-red windows, lenses, and filters. cryogenic thermometer	-bistable cryosars -cryosistors -photomagneto-electric (PME) light detector -thermoelectric power generator, when alloyed with silicon	-Ge is perhaps the most important of presently known semiconductors. It is also the most widely studied from the research point of view (3). -Ge has the distinction of being the purest of all solids. The impurity concentration in the best germanium is now about one part in 10^{10} (2). -Thin polycrystalline films of germanium form oxide layers rather rapidly when exposed to air (3). -Ge acts much the same as glass when hit or dropped. The same is true for silicon and for tellurium (3). -Liquid germanium has been shown to be a metal (3). The melting point of Ge is 940^{o}C.
50. GeS	1.8 (18)	-	-	-	Both 816 and 829 types noted (18)	yellow-red amorphous, or black (5)	1	-	-	-	-
51. GeSe	-	-	-	-	tetr. (18); orthor. (3259)	-	1	-	-	-	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
52. GeTe	-	-	see comments	-	B1+ (18)	-	1	-	-	thermoelectric applications	GeTe has always emerged as a p-type material. It was recently discovered as a thermoelectric material. It shows some promise of future importance in this field, especially when some Bi^{+3} is substituted for some Ge^{+2}, in order to lower the carrier concentration. Thus, a composition 95% GeTe, 5% Bi_2Te_3 is almost twice as efficient as is the GeTe by itself **(23)**.
53. HgI_2	-	-	-	-	C13 **(18)**	red crystals (4)	0	-	-	-	-
54. HgS	2 **(2)*** **(13)**	-	-	-	B3 **(18)** also hex. (5)	cubic, black; hex., red (5)	-	-	-	-	-
55. HgSe	0.16 **(18)** 0.6 **(32)** ^{r} **(13)**	**5.8** **(13)**	15,000 **(18)** 18,000 (2) **18,500** **(13)**	-	B3 (9) **(18)**	gray plates (5)	1	-	-	**infra-red detector (11,513)**	HgSe is an extremely volatile compound semiconductor (9); it is highly toxic **(15)**.
56. HgTe	0.02 (9) **(32)** (3501) * (3502) ^{r}	-	16,000 (3502) 17,000 (3501) 20,000 (2) 25,000 **(18)**	200 (2) **160** **(13)**	B3 (9) **(18)**	-	5	-	-	-	The high mobilities of HgSe and HgTe seem to confirm the remark that maximum mobilities occur in compounds having a slight ionic component in thei bonding **(18)**.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
57. I	1.3 (2)^r	-	-	~25 (2)	orthor.	heavy, grayish-black plates or granules; metallic luster; poisonous, corrosive (4)	1	-	-	-	Optical investigations showed iodine single crystals to be a semiconductor with a large activation energy (6998).
58. InAs	0.33 (1)^r (32)^r 0.36 (12)^r (38)^r 0.37 (31)^r 0.45 (2)*	11.7 (16) (22)	20,000 (11) 22,600 (31) 23,000 (1) (20) 30,000 (2) 33,000 (38) 50,000 (22)	100 (1) (20) 200 (11) (31) 240 (22) 250 (2) 500 (38)	B3 (38)	-	13	X	Hall generator	-thermistors -transistors -magneto-resistance devices -thermoel. studies -tunnel diodes	-The small energy band gap tends to make InAs unsuitable as a transistor material for room temperature operation (38). Valence electrons activated across the small band gap would tend to swamp any modulation of carrier concentration that might be induced by electrical means. -InAs and the other III-V semiconductor compounds have been examined for use as possible thermoelectric materials. In their favor are their unusually high electron mobilities and low effective masses; in their disfavor are their rather high thermal conductivities and small energy gaps (23). The ternary compound, $InAs_{1-x}P_x$ has a higher figure of merit, Z, for certain values of x than has the simple binary compound, InAs (23).
59. InP	1.25 (1)^r (4679) 1.28 (38)^r 1.3 (2)* (11)^r 1.34 (12)*	10.9 (16) (13)	3400 (1) (20) 3500 (11) 4600 (2) 5000 (38)	100 (2) 150 (20) (38) 650 (1) 700 (11)	B3 (14)	-	9	-	-	-solar cells -photocells -infra-red optics -high temp. rectifiers and transistors -electro-luminescence	InP has been reported to show transistor action (38). Actually, transistor action has been observed in a number of materials, but usually only under special conditions (39). See, for example, the comments for InSb, below.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
60. InSb	0.17 (11)^r (16)^r (31) 0.18 (1)^r (2)^r (38)^r 0.25 (2)* (16)* 0.26 (723)*	15.9 (3) (16) (22)	75,000 (22) 77,000 (1) 78,000 (38) 80,000 (2) (11) (20)	780 (31) 800 (38) 1250 (1) (22) 1400 (2)	83 (14)	-	39	X	-infra-red detector, 1-6 microns, with cooling used	-thermoelectric studies -tunnel diodes -photodiodes -transistors -photovoltaic cells -PME device -Hall generator -thermistors -magnetodiodes -magnetoresistance voltage regulator	InSb is the most extensively studied member of the group III-V compounds (16). It is relatively easy to prepare as a single crystal, with purity levels one to 3 orders of magnitude higher than that available for the other III-V compounds (16). Compounds in which the band gap is very low have been found generally to be less sensitive to the presence of impurities (38). InSb has the highest known electron mobility at room temperature; however, it loses this honor to PbTe at temperatures below 20^{o}K (2). InSb has a room temperature resistivity of about 0.02Ω-cm. (highest value to date). This compares with intrinsic resistivities at 27^{o}C of 47 Ω-cm. for Ge and 3 x 10^5Ω-cm. for Silicon (3). The small energy band gap of InSb seriously impairs its use in devices to be operated at room temperature. Such devices would be very temperature sensitive. Any transistor made of InSb would be useful only at low temperatures.
61. InSe	1.05 (38)^r	-	900 (38)	-	-	-	1	-	-	-	-
62. In_2Se_3	1.2 (18) (38)^r	-	30 (38)	-	83 (18)	-	1	-	-	-	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
63. In_2Te_3	0.88 (optical) 1.02 (electrical) (3429)	-	see comments	-	B3 (18) (20)	-	2	-	-	-	In_2Te_3 has a loose crystal structure, with many scattering centers. This results in a low value of mobility **(20)**.
64. K_3Sb	1.1 **(27)**	-	-	-	hex. **(27)**	yellow-green (5); highly toxic **(15)**	1	-	-	photoemission studies	The alkali metals form semiconducting compounds with antimony in the ratio of 3 to one; e.g., Na_3Sb; K_3Sb; Rb_3Sb; Cs_3Sb; and various multi-alkali materials, such as Na_2KSb. These materials are efficient photoemitters **(27)**.
65. Li_3Bi	-	-	-	-	DO_3 **(18)**	-	0	-	-	-	The crystal structure of Li_3Bi is a superposition of the fluorite (C1) and the rock-salt (B1) structures **(14)**.
66. Mg_2Ge	0.69 (2038)* 0.7 (1)^r 0.74 (2)*	-	280 (2036) 500 (2)	100 (2) 110 (2038)	anti-fluorite **(16)**	-	2	-	-	-	Mg_2Ge reacts with water vapor (11). This strong possibility of surface contamination could present reliability problems for devices made of this material.
67. MgO	7.3 **(16)** 7.4 (2)^r ~8.7 **(40)**	-	very little is known **(16)**	~2 (2)	B1 (3) **(18)**	white powder (4)	-	X	-	thermionic emission studies **(40)**	MgO is the most refractory of all the alkaline earth oxides, with melting point about 2500°C **(16)**. Its semi-conducting properties have received increasing interest of late, largely because of the availability of large, single crystals **(16)**.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
68. Mg_3Sb_2	0.82 $(1)^r$ (2)*	-	20 (2)	80 (2)	-	metallic (5)	0	-	-	-	-
69. Mg_2Si	0.7 $(1)^r$ 0.77 (2)*	-	~400 (2) (2039)	56 (2039) 70 (2)	C1 (5)	-	1	-	-	-	Mg_2Si reacts with water vapor(11).
70. Mg_2Sn	0.3 $(1)^r$ 0.35 (2)*	-	300 (2)	250 (2)	C1 (5)	-	2	-	-	-	Mg_2Sn reacts with water vapor (11). It is difficult to get pure enough material to determine E_g accurately (2). The II-IV compounds typified by Mg_2Sn, attracted attention a few years ago in the search for infra-red materials (2).
71. MgTe	-	-	-	-	B4 (18)	-	2	X	-	rectifiers	
72. $MnAl_3$	~0.58 (41)	-	>200 (41)	~200 (41)	-	-	1	-	-	thermoelectric studies	-
73. MnO	0.5 (18) 1.25 (20)	-	-	-	B1 (3)	grass-green powder (4)	-	-	-	-	MnO is used for medicine, ceramics, dry batteries, paints, colored glass, textile printing etc. (4).
74. MnSe	0.1 (18)	-	-	-	B1 (18)	gray (5)	-	-	-	-	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
75. MnTe	-	-	-	-	B8 **(18)**	-	-	-	-	thermoelectric studies	MnTe was one of the first thermoelectric materials investigated for use in the $800^0 - 1000^0C$ range. Unfortunately, it had a rather low figure of merit, Z **(23)**.
76. MoO_3	-	high **(20)**	-	-	orthor. (5)	white-yellowish or colorless (5)	-	-	-	-	MoO_3 has a high dielectric constant and an extremely small Hall effect **(20)**.
77. MoS_2	1.45 (2)*	-	-	150 (2)	hex. (5)	black, lustrous powder (4)	-	-	-	-	MoS_2 finds use as a lubricant in greases, oil dispersions, etc., especially under conditions of extreme pressures and high vacua (4).
78. Na_3Sb	1.1 **(27)**	-	-	-	hex. **(27)**	blue (5)	1	-	-	photoemission studies	See the comments for K_3Sb
79. NiO	1.7 to 1.9 **(20)**	-	on the order of 10^3 **(42)**	-	B1 (3)	green powder, becoming yellow (4)	-	X	-	thermoelectric generator **(30)**	NiO is of interest because by simple band theory, it should exhibit metallic conduction; instead, it is almost an insulator (2). Mobilities of over 800 cm^2/volt-sec. have been reported (2).
80. P	0.33 (2)*	-	220 (2)	350 (2)	orthor. (3)	black lustrous crystals, resembling graphite (4)	-	X	-	-	Phosphorus exists in several allotropic forms - white, red, and black (4). The latter form is probably a semiconductor (2).

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
81. PbS	0.34 (18) 0.34 to 0.37 (1)^r 0.37 (3) 0.39 (2)^r	unusually high (2)	400 (3) 500 (2) 600 (1) 650 (31) 800 (18)	200 (1) 250 (31) 500 (2)	B1 (14) (18)	black, with a strong metallic sheen (3)	16	X	infra-red detectors photoconductivity cells	thermoel. devices transistors (39)	The mineral galena, which is naturally occurring PbS, had historical significance in showing non-ohmic properties, and as use as a catwhisker detector (6). The combination of low energy gaps and high mobilities have made PbS, PbSe, and PbTe very useful as infra-red detectors (2). See comments for PbSe.
82. PbSe	0.25 (18) 0.27 (1)^r (2)^r	unusually high (2)	900 (1) 1200 (18) 1400 (2)	700 (1) 1400 (2)	B1 (18)	cr. (15)	6	-	infra-red detectors (below 9 microns)	thermoel. devices	Values of mobility for the 3 compounds, PbS, PbSe, and PbTe have been found to vary considerably between different specimens. The quoted values are order of magnitude of the maximum value. In any given sample, u_n is always greater than u_p, although of comparable magnitude (2).
83. PbTe	0.22 (18) 0.25 (3) 0.30 (1)^r 0.33 (2)^r	unusually high (2)	1300 (3) 2000 (2) 2100 (18)	300 to 400 (3) 2000 (2)	B1 (18)	white (5)	14	-	-infra-red detectors (below 9 microns) -thermoel. power generator	magneto-tunneling studies, using PbTe tunnel diodes (9)	At temperatures below 20^{0}K, PbTe has a higher mobility than any other material (2). An electron mobility as large as 4 X 10^6 cm^2/volt-sec. has been observed at 4.2^{0}K in a PbTe crystal with an electron concentration of about 6 X 10^{17}/cc. (43). PbTe has been used as a thermoelectric power generating material for over 10 years (23). However, it is an extremely brittle material (30), has a tendency to oxidize (30), ahd is confined to use at relatively low temperatures. A discussion of the possible causes for the widely differing values of E_g obtained by thermal measurements at elevated temperatures as opposed to optical measurements at room temperature on the compound PbTe is given in the literature (44).

SEMI-CONDUCTORS	E g (ev)	ξ	MOBILITY (cm²/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
84. Rb_3Sb	1.0 **(27)**	-	-	-	hex? **(27)**	-	-	-	-	photoemission studies	See the comments for K_3Sb
85. S	-	-	-	-	orthor. (5)	yellow crystals (4)	-	-	-	-	Sulfer is one of the best insulators in the dark, having a dark conductivity of the order of $10^{-18}\Omega^{-1}cm.^{-1}$. However, it shows marked photoconductivity when illuminated (especially with blue light), with conductivity increasing 3 to 6 orders of magnitude **(20)**.
86. Sb	-	-	-	-	rhomb. (3)	silver-white, lustrous, hard, brittle metal (4)	2	X	-	low current, extremely fast acting switches, suitable for computer networks **(21)**	Antimony is one of the semi-metals. It is almost metallic, but does show some semiconductor properties. A binary alloy, consisting of bismuth and between 5 and 30% of antimony has been found to be a semiconductor with a very small energy gap (2).
87. Sb_2S_3	1.7 $(2)^r$ **(18)**	-	15 (2)	45 (2)	$D5_8$ **(18)**	black crystals as the mineral stibnite; orange-red crystals as a precipitate (4)	1	X	-	-	Sb_2S_3 finds use in such things as pigments, pyrotechnics, matches, ruby glass, fireproofing fabrics and paper, etc. (4).
88. Sb_2Se_3	0.82 (4653) 1.2 $(2)^r$ **(18)**	-	15 **(16)** **(18)**	45 **(16)** 270 (2)	$D5_8$ **(18)**	gray cr. (5)	2	-	-	infra-red sensitivity studies	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
89. Sb_2Te_3	0.3 (2)^r **(18)**	-	-	~270 **(16)**	C33 (9) **(18)**	gray (5)	2	-	-	-	-
90. Se	0.8 **(20)** 1.5 (3) 1.8 **(18)**^{r} **1.6** **(8422)**	-	see comments	<1 in many specimens (3) ~10 (2)	hex. (2) (3)	steel-gray; very high luster; cr. surface on being broken (4)	15	X	-rectifiers -solar cells -photoconductive cells		Selenium and its compounds are quite poisonous, like arsenic (4). The photoconductivity of selenium was discovered in 1873 (6). It was perhaps the first semiconductor to achieve real importance **(20)**. Although studied in great detail, selenium remains one of the most complicated and least understood of all the semiconductors (3). Selenium is always p-type (2); **(29)**.
91. Si	1.10 (1)^r **(31)**^{r} **(32)**^{r} 1.21 (2)* (3)*	11.7 (586) 11.8 **(22)**	1200 **(22)** 1300 (2) 1350 **(31)** 1600 (1) **1900** **(13)**	400 (1) 480 **(31)** 500 (2) **(22)**	diamond	metallic lister, darker in hue than germanium (3)	82	X	-diodes -photodiodes -tunnel diodes -varactor diodes -power rectifiers -transistors -4-layer switching devices -solar cells -photoswitches -detector for neutrons and for charged particles -strain gages -microminiaturized functional blocks -infra-red windows and lenses	cryosars (10,778) delay lines **(45)**	Silicon has a thermal conductivity that is extraordinarily high for a non-metallic substance (11). Silicon is second only to germanium in having the highest purity of all the solids (2). It is now possible to grow silicon (and germanium) crystals virtually free from dislocations. "Perfect" specimens weighing as much as 50 grams have already been made **(46)**. Silicon has proven to be a useful material for the study of crystal dislocations. This is a consequence of its transparency to infra-red radiation, and man's ability to grow relatively perfect crystals of silicon. Therefore, by using infra-red radiation along with a suitable decoration (e.g., a copper impurity), it is possible to observe individual dislocations in silicon crystals **(46)**. Silicon is much more refractory than is germanium; its melting point is 1420^{0}C (3).

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
92. SiC	2.8 **(36)** 2.86 **(16)** **(13)** ~3.0 (3) 3.3 (11)^r ------ 1.9 for the zinc blende type; 3.0 for the hex. type (2)* ------	6.7 **(20)** **(13)** 10.2 (586)	~ 100 (2) 60 **(13)**	~50 (2) ~8 **(13)**	83 with at least 10 modifications (3); also hex.	transparent crystals when pure (2)	27	X	-symmetrical varistors -rectifiers for high temperature use -abrasives	-transistors for high temp.use -resistance heating elements, often used for infra-red sources (3)	SiC is a highly refractory material. It decomposes at about 2200°C (3). Refractory materials such as SiC may be quite resistant to surface contamination (11). Commercially produced SiC crystals cover a wide range in color, from white to yellow to green to black. They also have a wide range of electrical and mechanical properties. The green and yellow crystals are often n-type semiconductors; the black crystals are usually p-type (3). Efforts to make reproducible, large size single crystals of SiC, suitable for electronic work, have proven disappointing, despite much effort. This may lessen interest in it as a transistor material **(39)**. The main electrical applications of SiC at the present time, such as lightning arrestors, depend more on the nonlinear resistance characteristics of the contacts between individual grains than on the bulk properties (3).
93. Sn	0.068 (3496) 0.08 (1)^r (2)* (3) **(16)**	50 **(20)**	2500 (2) 3000 **(20)** **(38)**	2400 (2)	diamond (3)	gray, brittle (4)	6	X	-	-	Gray tin is the stable form of tin below 13°C; it has the diamond structure. White tin is stable above 13°C; it has a tetragonal structure. The conversion from white to gray tin takes place very slowly at temperatures only slightly below 13°C. The conversion rate is a maximum at -40°C. Addition of a few tenths of a percent of bismuth inhibits the conversion almost completely (3). Because the conversion is a solid-solid process resulting in a large change in volume, the gray tin product is in a poor mechanical condition, full of holes cracks, and lattice defects. There is no liquid phase of gray tin (3) . However, a method of growing gray tin single crystals from a liquid amalgam is presented in the literature **(47)**.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
94. SnS	1.08 (48)^r	19.5 ±2 (48)	-	~90 (48) see comments	B29 (18)	dark-gray or black cr. powder (4)	1	-	-	-	The hole mobility at room temperature in a plane perpendicular to the c-axis was found to be about 90 cm^2/volt-sec., whereas it was about 5 times smaller in the direction of the c-axis (48).
95. SnS_2	-	-	-	-	C6 (18)	yellow to brown powder (artificial gold) (4)	0	-	-	-	SnS_2 is a semiconductor; however, most compounds of AX_2 composition are predominantly ionic (14).
96. SnSe	-	-	only p-type reported (6132)	100 (6132)	B29 (18)	steel-gray cr. (5)	1	-	-	-	SnSe has a sheet-like crystal structure, behaving similar to mica. The cleavage planes are perpendicular to the c-axis. (4280).
97. SnTe	-	-	-	-	B1 (18)	gray cr. (5)	3	-	-	thermoel. applications when alloyed with PbTe (23)	-
98. Te	0.33 (2)* 0.34 (3) (20)	23 (3)	1500 (20) 1700 (2)	1200 (2) (20)	hex. (3)	silver-white metallic with a high reflecting power for visible light. (3) (can be depilatory) (4)	10	-	-	-thermoel. devices (4)- -photo cathode material, in combination with rubidium (23)-	Tellurium is known for its peculiar Hall effect inversion. A p-type sample at low temperatures may make an apparently normal conversion to n-type when passing from the impurity to the intrinsic range of temperature. At still higher temperatures, the Hall coefficient reverses sign again, and the material is once again p-type (3). Tellurium becomes metallic at 44,000 atm. pressure (7).

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT - SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
99. TiC	-	-	-	-	B1 (5) **(49)**	cr.solid, with a gray, metallic color (4)	0	-	-	-	TiC is of interest because of its extreme hardness, about equal to that of SiC, and its high melting point, 3250°C **(49)**. Experiment has shown that oxygen-free TiC (deposited on an Al_2O_3 substrate) has a metallic behavior, while, with a slight uptake of oxygen (by depositing on a SiO_2 substrate), TiC shows semi-conductor properties with a negative temperature coefficient **(49)**.
100. TiO_2	~3.0 (2)* 3.05 **(20)**	see comments	0.2 (2) ~1 (3) **(20)**	-	C4 (rutile) **(18)**	white to black powder, depending on purity (TiO_2 has the greatest hiding power of all the white pigments) (4)	12	X	-	-rectifiers for high temp. use -single crystals are high temp. transducers (4)	Rutile has the highest density and is the most stable of the 3 crystal forms for TiO_2 - i.e., anatase, brookite, and rutile **(20)**. Rutile is widely known as a sparkling gemstone. Its index of refraction is about 2.5 (3). Rutile is noted for its high dielectric constant - about 83 in a direction perpendicular to the principle axis, to about 167 in a direction parallel to the principle axis **(20)**. Some investigators have found that the dielectric constant decreases slightly with temperature, going through a minimum value at about 150 - 200°C, after which it begins to rise very rapidly. There are indications that its value for temperatures above 600°C may be 10 or 100 times greater than its room temperature value **(42)**. The extremely low values quoted for electron mobility are subject to perhaps large revision when TiO_2 of more near-stoichiometric composition is considered **(42)**.
101. Ti_2O_3	-	-	-	~3 (7309)	$O5_1$ (5)	violet-black (5)	1	-	-	-	Ti_2O_3 can be made by partially reducing rutile with hydrogen **(20)**.

SEMI-CONDUCTORS	E_g (ev)	ε	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
102. TiS_2	-	-	-	-	C6 (5)	yellow scales (5)	1	-	-	measurements to determine effect of pressure on resistivity (7)	-
103. TiS_3	-	-	-	-	-	-	1	-	-	measurements to determine effect of pressure on resistivity (7)	-
104. $TiSe_2$	-	-	-	-	C6 (5)	-	1	-	-	measurements to determine effect of pressure on resistivity (7)	$TiSe_2$ may possibly be metallic, although its resistivity is rather high for a true metal (7).
105. Tl_2S	-	-	-	-	-	blue-black, lustrous, microscopic crystals or amorphous powder; poisonous (4)	-	-	-	photoconductive and photovoltaic cells (infra-red sensitive photocells) (4)	Tl_2S shows semiconducting properties right up to its melting point, and retains these properties without any marked quantitative changes even after melting (20). Thallium sulfide is one of the most sensitive photoconductors. However, photocells made from it tend to lose their photo-sensitivity after only a few months use (20).

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
106. TlSe	0.57 (9)	-	-	25 to 50 (9); also, 600 reported elsewhere (9)	B37 **(18)**	single crystals (9)	2	-	-	-	TlSe has a low melting point - only 330°C (9).
107. UO_2	-	-	-	-	-	black crystals (4)	-	-	-	thermistors **(20)**	UO_2 has a relatively high temperature coefficient of resistivity. This, plus its great stability, make it a possible thermistor material **(20)**.
108. V_2O_3	-	-	see comments		$O5_1$ (5)	black crystals (4)	1	-	-	-	Mobility values of about 0.01 cm^2/volt-sec. have been reported for V_2O_3 (2).
109. WO_3	-	high **(20)**	very small **(20)**	-	-	canary yellow, heavy powder (4)	-	-	-	-	In spite of its n-type conduction, WO_3 has an extremely high contact potential, exceeding that of gold. As a result, a junction between WO_3 and a p-type semiconductor might not give a rectifying barrier layer **(20)**.
110. $ZnAs_2$	0.90, $E \parallel C$; 0.93, $E \perp C$ **(25)**	-	-	50 **(25)**	monocl. primitive unit cell (3726)	-	1	-	-	-	The electrical and optical properties of $ZnAs_2$ show marked anisotrophy **(25)**.

SEMI-CONDUCTORS	E_g (ev)	ε	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
111. Zn_3As_2	0.93 (25)^r (7027)^r	-	-	10 **(25)** < 30 (7027)	05_9 (9)	-	1	-	-	-	- Zn_3As_2 is highly toxic (15).
112. ZnO	~3.0 (4921) 3.2 (2)^r 3.4 **(18)**	B.5 **(16)**	150 to 200 (2) 1000 **(18)**	see comments	B4 **(18)**	white or yellowish-white powder (4)	5	X	-	-	ZnO is always n-type **(29)**.
113. ZnS	3.6 **(18)** 3.B (2)* 3.5B to 3.67 for the B4 structure (3)*	**5.13** (13)	100 **(18)** **(13)**	see comments	B3 and B4 (3)	yellowish-white powder (4); also, colorless crystals	23	X	- phosphors - electro-luminescent cells	- crystal detectors	ZnS is always n-type (2). Zinc-blende crystals (B3 form of ZnS) are known to be piezo-electric (9). Electroluminescent ZnS:Cu:Cl behaves like a highly ionic semiconductor (6080).
114. ZnSb	0.3 (6363) 0.49 **(50)** 0.53 **(25)**^{r} 0.56 (1)^r (2)*	-	-	300 (2) 350-575 **(25)**	-	-	2	-	-	thermoel. material	ZnSb was known over 100 years ago, but was "rediscovered" as a thermoelectric material in 1936. **(23)**. Better quality ZnSb crystals have been produced recently, yielding higher values of mobility than those quoted previously **(50)**.

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
115. ZnSe	2.58 (18) 2.60 $(1)^r$ 2.67 $(32)^r$ 2.8 $(2)^r$	5.75 (13)	~100 (18) 260 (13)	16 (13)	B3 (18)	yellow, rod shaped crystals were grown (51)	5	-	-	-	ZnSe is widely used in cathode-luminescence. It has high photo-sensitivity (7397).
116. ZnTe	0.85 $(2)^r$ 2.1 (13), $(32)^r$ 2,2 (18)	~9 (13)	-	50 (13)	B3 (18)	red (5)	6	-	-	photoconductivity studies	**ZnTe has potential value in high temperature applications (52).**
117. ZrO_2	-	-	-	-	hex. (5)	heavy white amorphous powder (4)	-	X	-	-	ZrO_2 is a commercial refractory material of very high heat resistance (4).
118. ZrS_2	-	-	-	-	C6 (5)	steel-gray cr. (5)	1	-	-	measurements to determine effect of pressure on resistivity (7)	-
119. ZrS_3	-	-	-	-	-	-	1	-	-	measurements to determine effect of pressure on resistivity (7)	-

SEMI-CONDUCTORS	E_g (ev)	ξ	MOBILITY (cm^2/ VOLT-SEC)		CRYSTAL STRUCTURE	PHYSICAL APPEARANCE	KNOWN NUMBER OF RESEARCH GROUPS	THIN FILM	APPLICATIONS		COMMENTS -
			μ_n	μ_p					COMMERCIAL DEVICES	LAB STUDY	
120. $ZrSe_3$	-	-	-	-	-	-	1	-	-	measurements to determine effect of pressure on resistivity (7)	-
121. $ZrTe_2$	-	-	-	-	-	-	1	-	-	measurements to determine effect of pressure on resistivity (7)	$ZrTe_2$ may possibly be metallic, although its resistivity is rather high for a true metal (7).

Additional Comments

A few additional comments are given below concerning the data of Table I:

1. It is quite apparent, from Table I, that different investogators get different results for the values of the intrinsic constants of the various semiconductors. This follows directly from the fact that the measured values of the intrinsic constants, expecially the mobilities, are extremely sensitive to the quality of the material. Probably the purest materials available are germanium and silicon, with only InSb approaching them in purity (2). Therefore, the range in values noted for these constants should not be surprising, since a very high degree of crystalline perfection is required in order to find the true intrinsic values.

2. Interest in the field of semiconductors is so widespread that any listing of laboratory or commercial devices made from them must necessarily be incomplete, since no one investigator can know what all the other investigators in his field are doing. An example of this interest is noted in that it is estimated that there are up to 1,000 companies and groups (many not in the electronics industry) active in the field of thermoelectric devices alone (54).

3. There are 12 elements now known to show semiconducting properties:

   Germanium
   Silicon
   Carbon
   Tin
   Boron
   Selenium
   Tellurium
   Phosphorus
   Arsenic
   Antimony
   Sulphur
   Iodine

   The last five (phosphorus, arsenic, antimony, sulphur, and iodine), while showing semiconductor properties, are not usually considered as semiconductors. Arsenic and antimony are generally thought of as metals, while phosphorus, sulphur, and iodine are generally thought of as insulators (3).

4. One of the striking features of the more important compound semiconductors is their moderate-to-high degree of toxicity. In some cases, this may be the fault of the cation, e.g., in compounds of mercury or lead. However, an examination of the semiconductors in Table I will reveal that most of the important compound semiconductors seem to fall into the following categories:

a. Antimonides
b. Arsenides
c. Oxides
d. Phosphides
e. Selenides
f. Sulfides
g. Tellurides

The antimonides, arsenides, phosphides, selenides, and tellurides are all more than moderately toxic (15). Additional hazards include, among others, the high vapor pressures of the selenides and tellurides (23), and the tendency of the phosphides to decompose to phosphine upon contact with moisture or acids (15). Sulfides tend to be much less toxic, although they can be a fire hazard, and they do tend to evolve hydrogen sulfide upon contact with moisture or acids (15). The oxides are the safest of the above mentioned groups, their degree of safety depending largely on the properties of the cation. An example of a practically nontoxic semiconductor is titanium dioxide, $Ti0_2$ (15).

5. The crystal structure types of the principle single element and binary compound semiconductors are given in Table II. It shows that semiconductivity is confined to no one structure type, even though certain types seem favored.

Table II. Crystal Structure Types of the Principal Single Element and Binary Compound Semiconductors

SYMBOL*		STRUCTURE* TYPE	CRYSTAL* SYSTEM	REPRESENTATIVE SEMICONDUCTORS
1.	B1	NaCl	cubic	CdO, GeTe, MgO, MnO, MnSe, NiO, PbS, PbSe, PbTe, SnTe, TiC
2.	B3	ZnS (zinc blende)	cubic	AlAs, AlP, AlSb, BAs, BN, BP, CdS, CdTe, GaAs, GaP, GaSb, Ga_2Se_3, Ga_2Te_3, HgSe, HgTe, InAs, InP, InSb, In_2Se_3, In_2Te_3, SiC, ZnS, ZnSe, ZnTe
3.	B4	ZnO (wurtzite)	hex.	AlN, CdS, CdSe, MgTe, ZnO, ZnS
4.	B8	NiAs	hex.	MnTe
5.	B29	SnS	orthor.	GeS, SnS, SnSe
6.	B37	TlSe	tetr.	TlSe
7.	C1	CaF_2	cubic	Mg_2Si, Mg_2Sn
8.	C2	FeS_2	cubic	FeS_2
9.	C3	Cu_2O	cubic	Cu_2O
10.	C4	SnO_2	tetr.	TiO_2
11.	C6	CdI_2	hex.	CdI_2, SnS_2, TiS_2, $TiSe_2$, ZrS_2
12.	C13	HgI_2	tetr.	HgI_2
13.	C33	Bi_2Te_3	rhomb.	Bi_2Se_3, Bi_2Te_3, Sb_2Te_3
14.	DO_3	BiF_3	cubic	Li_3Bi
15.	$D5_1$	Fe_2O_3	rhomb.	Al_2O_3, Fe_2O_3, Ti_2O_3, V_2O_3
16.	$D5_8$	----	orthor. (5)	Sb_2S_3, Sb_2Se_3
17.	$D5_9$	Zn_3P_2	tetr.	Cd_3As_2, Zn_3As_2

*Reference (18).

SECTION III

OTHER TYPES OF SEMICONDUCTORS

Ferrites

Although ferrites are semiconductors, having a practical range of resistivity between about 10^1 to about 10^9 ohm-cm., their possible use in semiconductor devices appears to have but little mention in the literature. Ferrites may eventually prove useful in particular semiconductor applications where a high value of magnetic permeability (u) is desirable. However, it appears that ferrite semiconductors would be rather complex compounds, with rather low mobilities (11). A practical difficulty, as with oxide materials in general, is the preparation of good single crystals (2). Articles describing the successful growth of single-crystal ferrites have appeared recently in the literature (55), (56).

Ternary Compounds

Another group of semiconductors includes the ternary compounds. Several of these compounds have been the subject of recent investigation, such as $CdSnAs_2$ (9). As yet, however, ternary compounds are relatively unimportant when compared to the simpler single element and binary element semiconductors.

Mixed Crystals and Alloys

Another group of inorganic semiconductors are those in which two or more semiconductors are combined to form alloys, solid solutions, or mixed crystals. These are becoming increasingly important in the field of thermoelectricity. (See, for example, the comments for Bi_2Se_3 and for GeTe. Another recently announced thermoelectric material (23) consists of an alloy of silicon and germanium.) The reason for this interest is that the performance of thermoelectric materials may be improved by using mixed crystals, since the disorder introduced into the crystal lattice may reduce the thermal conductivity more than it reduces the electrical conductivity (2).

A brief but relatively thorough review of semiconductor alloys, coupled with a large list of references, is available in the literature (57).

No discussion of materials for the optical maser is given in this survey. However, information concerning details of construction, applications, and materials for the optical maser may be found in the literature (58).

Organics

There is at present considerable interest in the field of organic semiconductors. This interest arises in large part because of the possibility of using an enormous quantity of new materials -- there are about 900,000 separate organic materials now classified (21) -- permitting the possible tailoring of electrical properties through organic chemistry. It is believed that between 20 and 30 laboratories in the United States are now conducting research in the field of semiconduction phenomena in organic polymers, with a similar interest being shown in Europe, particularly in Russia (59).

An organic semiconductor may be defined as a solid containing an appreciable number of carbon-carbon bonds, capable of supporting electronic conduction (60). A major goal of present-day research is to understand the mechanism of electronic conductivity in these materials and to relate these mechanisms to the structure of the solid. The present state of this understanding has been compared to that of inorganic semiconductors about 25 years ago (60).

Some success has been reported in the use of organic semiconductors in that current rectification, photovoltaic production and photoconduction sensitivity have been demonstrated in the lab. The conductivity of organic polymers has been found to range between 10^4 to 10^{-21} reciprocal ohm-cm. (59). However, much more work must be done with organic semiconductors before practical devices made from them can replace those made now with inorganic semiconductors.

Possibly the biggest difficulty in examining the properties of organic semiconductors arises from the fact that, in order to observe the basic semiconduction of organic crystals, purification techniques as extensive as those applied to inorganic molecules should be used (60). At one time it was hoped that such careful processing would be unnecessary. Values of mobility for organic materials have generally been found to be only moderate or low; therefore, such materials would not be useful in applications requiring a rather high value of mobility (e.g., a Hall generator).

Devices made of organic semiconductors may eventually prove practical. For example, anthracene is used in scintillation counters in nuclear physics experiments. In addition, current research in the field of organic semiconductors should add to our knowledge of electron transfer processes in molecular solids and to our understanding of certain important biological processes, such as photosynthesis. Reference (59) is a current state-of-the-art report in the study of organic semiconductors.

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586
723
2035
2038
2039
2377
3259
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3502
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4921
6066
6080
6132
6356
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6519
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* U.S. GOVERNMENT PRINTING OFFICE : 1962 O—653043

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