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Infrared (8-12 μm) Dome Materials: Current Status

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ABSTRACT

The 8-12 μm range of infrared radiation being very significant for various electrooptic applications, various materials present themselves as candidates for use as dome (window) materials in this range. This paper discusses various thermal, mechanical and optical properties of these materials. Further, trends in the development of these materials are also presented.

1. INTRODUCTION

Infrared systems find extensive applications in various civilian as well as military areas. These systems are generally classified as either (i) active systems or (ii) passive systems. The active systems involve illumination of the target with an IR radiation of a suitable wavelength and then receiving and analysing the reflected beam. The passive systems operate on the basis of the principle that every object emits infrared radiation at a temperature above zero K, the peak wavelength λ_{max} being determined by the temperature of the body. In either system, the reflected or the emitted radiation is collected on a suitable IR detector, after passing through the optics of the system which collimates it with minimum transmission loss. The collimating system includes various components, such as lenses, prisms, filters, protecting windows and domes.

Various materials have been utilised for the fabrication of these IR transmitting components. These materials differ widely in their transmission ranges, mechanical and thermal properties and stability. A good account of the relationships between the transmission behaviour of a material

and its various structural and mechanical properties has been given by Donald and McMillan¹. Depending upon the application, materials with a certain predetermined set of properties are chosen for the fabrication of the component. Thus, whereas in certain IR laser applications, materials showing high transmission values are required, in the case of IR dome fabrication, materials with high transmission as well as sturdy thermal and mechanical properties are desirable. Refractive index of the material also plays an important role in determining its suitability for a particular application. Materials with low refractive index can be used for narrow magnification and narrow field of view, but for a wider field of view, materials with high refractive index are required. High refractive index leads to high reflection losses, but this problem can be overcome with the use of anti-reflection coatings.

Most of the IR systems make use of the fact that atmosphere shows three IR transmission ranges, viz., (i) 1-2.4 μm (ii) 3-5 μm , and (iii) 8-12 μm . Most of the optical glasses transmit in 0.1-2.5 μm range. However, for the 3-5 μm and 8-12 μm ranges, special materials are to be selected.

These two ranges are of significant military importance, as these are the IR ranges in which bodies at several hundred degrees and at a temperature in the vicinity of 30 °C emit, respectively. Though, a wide range of materials, including ceramics and glasses are available for fabrication of windows in 3-5 μm range¹, relatively few materials are available for fabrication of domes/windows in 8-12 μm range, which can be used in missile-homing seekers and other airborne IR optical systems. Even, these materials show limitations while considering the future aircraft and supersonic missiles flying at a speed of > 3 Mach. The materials used in fabrication of domes/windows in 8-12 μm range are required to have good transmission behaviour (improved further by the application of antireflection coatings) coupled with good thermal, mechanical, thermomechanical, thermo-optical and electrical properties. This combination of properties puts a severe restriction on the choice of materials available for the fabrication of domes/windows in 8-12 μm range.

Currently, *ZnS*, *ZnSe*, *Ge* and *GaAs* are the materials which are being utilised in this region. Calcium lanthanum sulphide (*CaLa₂S₄*) is being investigated as a potential candidate. Diamond, however, remains the most attractive material because of its excellent properties. Diamond can be used either as an antireflection/protective coating on the conventional IR transmitting materials, e.g. *ZnS* or itself as a free standing IR transmitting window. Efforts are on to explore the possibility of using diamond (type-II) by making it available in thicker layer or bulk form. This article reviews the methods of preparation of these materials as well as their present status.

2. METHODS OF SYNTHESIS

2.1 Zinc Sulphide

Zinc Sulphide (*ZnS*) is the most suitable among the present generation of materials for transmission in 8-12 μm range under conditions where temperatures of several hundred degree centigrade are to be encountered. Though single crystals of

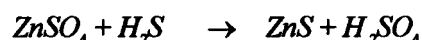
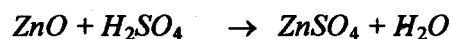
ZnS have been grown, their use in IR window fabrication has been restricted owing to the high melting point (accompanied by dissociation) of *ZnS* leading to the complexities of the process involved. Moreover, fabrication of a suitably-shaped body from a single crystal proves to be a tedious process. As a result, polycrystalline *ZnS* body is utilised in the fabrication of IR window. Polycrystalline *ZnS* body can be produced in two ways: (i) synthesis of *ZnS* powder through different conventional chemical reactions followed by its compaction using hot pressing or hot isostatic pressing (HIP), and (ii) chemical vapour deposition (CVD) of *ZnS* on a suitably-shaped substrate through a vapour phase reaction. The body formed can be further strengthened/compacted by an HIP technique.

2.1.1 Conventional Chemical Reaction Routes

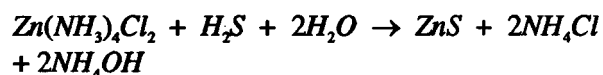
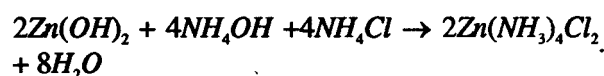
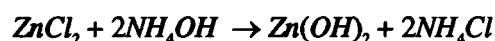
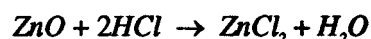
ZnS powder has been prepared through different chemical routes. Notable among these are: (i) aqueous chemical reactions involving a soluble *Zn* salt and *H₂S*, thiourea or thioacetamide and (ii) vapour phase reaction between elemental *Zn* and *S* in a closed ampoule. Of these, the former have been investigated thoroughly, even though the literature on both these routes is scanty.

A number of workers have studied the *ZnSO₄* (aq)-*H₂S* reaction. Two subprocesses have been developed as a result: (i) acid process, and (ii) alkali process. These two processes differ in the pH conditions of the reactions. The reactions involved in the two processes are:

(a) Acid Process



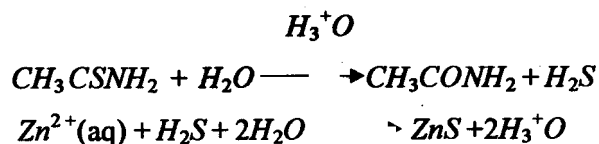
(b) Alkali Process



The acid process is considered to be better suited, as the alkali process is known to introduce undesirable hydroxide species². Eastman Kodak has used acid process. After purification, the ZnS is hot pressed to give a transparent body marketed as IRTRAN-2.

ZnS powder³ is produced by the reaction of $ZnSO_4$ with thiourea also, but the powder is contaminated with undesirable hydroxide impurities and hence has little use in fabrication of IR windows.

Zn salt reaction with thioacetamide has been investigated and uniformly-shaped spherical particles have been formed⁴. The method involves the following reactions:



These powders have been found to give on compaction near-theoretical density bodies. However, IR transmission behaviours of these compacts have not been discussed⁵. Production of ZnS powder by vapour phase reaction of elemental Zn and S has been studied⁶. However, IR transmission characteristics as well as other physical properties of these powders have not been investigated.

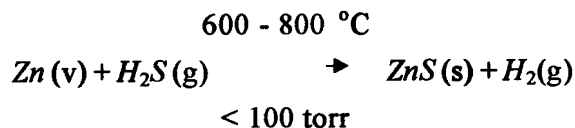
Very little information is available on hot isostatic pressing/(HIP) of ZnS powder. Carnall⁷ of Eastman Kodak studied the effect of hot pressing conditions on the density of compact ZnS . Keizo Uematsu,⁸ *et al.* studied the effect of additives, such as Bi_2S_3 , Al_2S_3 and Li_2S on the grain size and density of hot pressed ZnS . Huffadiene⁹, *et al.*, discussed the HIP conditions of ZnS powder and concluded that in order to retain the transparency, the HIP sample is to be maintained under pressure while cooling. More recently, Xue and Raj¹⁰ investigated the effect of hot pressing conditions on the optical transmission of ZnS . They reached the conclusion that the relative proportions of two ZnS phases, viz., (i) cubic-sphalarite phase, and (ii) hexagonal-wurtzite phase, as well as the grain size

of the compacted body, play a crucial role in determining the IR transmission of the body.

2.1.2 Chemical Vapour Deposition

Chemical vapour deposition (CVD) technique was evolved as an alternative to meet new requirements of size, purity, durability and economics. Scientists working at Raytheon Co.¹¹ USA, pioneered the early work in this field.

Simply stated, CVD is a gas phase reaction which results in the deposition of a solid material on a suitably-shaped substrate or mandrel. Thus, Zn vapour and H_2S gas are allowed to react at an elevated temperature (600-800 °C) and reduced pressure (<100 torr) in a reactor. The reaction involved is:



The deposition rate can be in the range 10-100 μh . Thus, a period of almost three weeks is required for growing about 1 in. thick ZnS crust.

To improve upon the physical properties, the CVD-grown material has been subjected to HIP. The material thus obtained has been called multispectral material (showing transmission in both visible and IR regions). Savage,¹² *et al.* studied different characteristics of the multispectral material and the role of HIP parameters.

2.2 Zinc Selenide

2.2.1 Chemical Synthesis

Chemical synthesis of zinc selenide ($ZnSe$) in an aqueous solution is much involved compared to that of ZnS because of the instability of freshly precipitated $ZnSe$. This problem has been circumvented by dissolving Se in Na_2SO_3 solution and then making this solution react with Zn salt solution². Taylor¹³, *et al.*, reacted a mixture of Se , activated charcoal, KOH and $KH_2PO_2 \cdot 2H_2O$ (potassium hypo phosphite) in H_2O with $ZnCO_3$ to produce $ZnSe$. Korezynski¹⁴, *et al.* reacted Zn salts with K_2Se under H_2 atmosphere to precipitate $ZnSe$, which, however, is non-stoichiometric.

ZnSe powder has been prepared by reacting elemental *Zn* and *Se* in an evacuated¹⁵ *SiO*₂ ampoule at 450-750 °C. Hot pressing of the *ZnSe* powder has been standardised at Eastman Kodak and the resultant product has been marketed by them as IRTRAN-4.

2.2.2 Chemical Vapour Deposition

ZnSe is also produced by CVD technique. This technique is similar to that employed for preparing *ZnS*. The following reaction takes place in the reactor:

600-800 °C



< 100 torr

2.3 Zinc Sulphide/Zinc Selenium Sandwich Windows

ZnS is sturdier than *ZnSe* as far as physical (mechanical/thermal) properties are concerned. However, transmissionwise, *ZnSe* is superior to *ZnS*. Hence, *ZnS/ZnSe* sandwich windows have been developed involving a CVD-grown *ZnSe* substrate coated with a thin layer of *ZnS* to provide mechanical/thermal support¹⁶.

2.4 Germanium

Germanium (*Ge*) has been one of the earliest leaders in the field of IR transmitting materials because of its excellent transmission range. Single crystals of *Ge* used in the fabrication of IR windows are easily grown by Czochralski technique. In this technique, *Ge* is melted at 900-1000 °C in a large container and a *Ge* seed of the required orientation is lowered in the melt and then gradually withdrawn at a very slow rate. Bulk crystals of *Ge* up to 26 cm diameter have been grown.

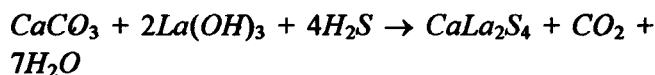
Polycrystalline *Ge* can also be grown by the Bridgeman technique in which the melt is gradually moved through a preset temperature gradient.

2.5 Gallium Arsenide

Gallium arsenide (*GaAs*), another versatile IR transmitting material, can be grown in single crystalline or polycrystalline form. Both Bridgeman and Czochralski techniques have been used. However, these conventional techniques lead to the growth of ingots of limited size only owing to the weak strength of quartz ampoules. Halfner and Braun¹⁷ made use of *He* vented ampoules to grow large crystals of *GaAs*. Kloeck¹⁸, *et al.* developed polycrystalline *GaAs* body by hot pressing *GaAs* powder (formed by grinding *GaAs* single crystal) to get over the problem related to its weak fracture toughness.

2.6 Calcium Lanthanum Sulphide

Calcium lanthanum sulphide (*CaLa₂S₄*) is one of the members of the family of ternary sulphides with the general formula *AB₂S₄* (where A is a divalent metal cation and B is a trivalent metal cation). This compound has recently been investigated and has been found to be a promising IR transmitting material in the 8-14 μm range^{19,20} besides being inexpensive. The material is synthesised in powder form through ceramic route. White,¹⁹ *et al.* used *CaCO*₃, *La(OH)*₃ and *H₂S* as the starting materials. They mixed the first two in stoichiometric ratio and then fired the resulting mixed powder in an atmosphere of *H₂S* at 1100 °C for 3-7 days.



Covino,²⁰ *et al.* have developed another technique, wherein a stoichiometric mixture of *Ca(NO₃)₂* and *La(NO₃)₂* in *HNO₃* is allowed to dehydrate and the resulting fine mixture of nitrates is treated with *H₂S* gas at about 900 °C to give *CaLa₂S₄* powder.

The *CaLa₂S₄* powder obtained through either of the above methods is then hot pressed/cold pressed to give green compact of > 55 per cent of theoretical density, which then is sintered in flowing *H₂S* gas at 1050-1200 °C to give a ceramic body of > 95 per cent of the theoretical density. This is then isostatically hot pressed 990-1200 °C

and at 172-200 MPa for 15 min to 3 hr to give a transparent body. The most suitable composition range has been found to be between $40CaS.60La_2S_3$ and $50CaS.50La_2S_3$.

2.7 Diamond

Diamond is the material considered to be the ultimate choice for window applications in the 8-12 μm range because of its excellent optical, thermal and mechanical characteristics. IR grade material diamond (type-II) was used in space optics as a window material in the pioneer Venus IR radiometer²¹.

Until early eighties, the synthesis of diamond was carried out using a high pressure-high temperature (HP-HT) process which led to the formation of diamond particles used mainly in grinding application²². However, in 1983, Kamo,²³ *et al.* synthesised diamond in a microwave plasma-assisted CVD process. Since then, a number of papers dealing with the growth of diamonds in a microwave plasma-assisted CVD process have appeared. Kobashi,²⁴ *et al.* reviewed this work up to 1987 (including the earlier processing work done by the Russians in the field of diamond synthesis using chemical transport reaction (CTR) method, gaseous phase decomposition, etc.) and presented an exhaustive account of this work.

Setaka,^{23,25} *et al.* investigated three types of CVD methods for diamond synthesis: (i) hot filament method, (ii) rf-plasma CVD method, and (iii) microwave plasma CVD method. In the hot filament CVD setup, a *W* filament placed about 10 mm above the substrate is electrically heated to about 2000 °C. The quartz tube reaction chamber is placed in a furnace at ~ 600 °C. Because of hot filament radiation and furnace radiation, the substrate gets heated to about 1000 °C and various surface processes, e.g. molecular dissociation, diffusion, chemical reactions, etc. get activated. The hot filament creates atomic *H* and various active fragmentary hydrocarbon species, (ions, radicals) by dissociating molecular H_2 and CH_4 . These active species having long life times, travel to the substrate surface causing growth of diamond.

In rf-plasma CVD setup, a hydrocarbon-hydrogen mixed gas plasma is generated, by way of irradiation by rf-plasma wave, and as a result diamond grows on the substrate.

Microwave plasma CVD setup is similar to the rf-plasma setup, except that plasma is generated by microwaves. The mechanism of diamond formation in microwave plasma CVD, which is currently receiving maximum attention is not fully understood. According to a mechanism for diamond synthesis proposed by Setaka²⁶, CH_4 and H_2 are dissociated in plasma and chemically active fragmentary hydrocarbon ions, radicals and atomic *H* are generated. The former migrate to the substrate and are adsorbed. Initially, *C* clusters are formed that have predominantly graphitic and amorphous structures because of thermodynamic considerations. However, metastable diamond structures are also formed. Since graphite-hydrogen reaction is very fast, graphite-cluster structures are quickly removed, whereas diamond structures stay and grow.

Whereas CH_4-H_2 mixture has been employed in thermal and hot filament CVD techniques, other hydrocarbon gases, such as C_2H_2 , C_2H_4 , C_2H_6 , have also been used in microwave plasma CVD techniques.

Recently, Ravi²⁷ reported high deposition rate synthesis of diamond using a technique involving $C_2H_2-O_2$ combustion reaction, which activates excess C_2H_2 in the gas mix, leading to deposition of a diamond film on a temperature-controlled substrate. Harris²⁸ reported the production of 0.3-1.0 mm thick clear diamond windows having diameters up to 6 cm.

3. PHYSICAL (OPTICAL, THERMAL & MECHANICAL) CHARACTERISTICS

Materials required for fabrication of IR windows in 8-12 μm range should be mechanically robust, thermal shock resistant and thermally conducting (so as to have minimum heating effect) and of course, be excellent transmitters in this

range. It is needless to say that existing materials do not possess ideal characteristics in all areas of requirement. In fact, some characteristics vary in opposite direction. For example, materials possessing strong bonds between constituent atoms show very good mechanical characteristics, but the transmission range becomes narrow and the cutoff wavelength shifts towards shorter wavelengths. On the contrary, materials having weak inter-atomic bonds (and consequently poor mechanical properties) show a longer transmission range. Thus, a trade-off has to be resorted to while choosing a material for a particular application. However,

though still in the development stage, diamond remains an excellent potential material with excellent all-round characteristics, except for two absorption bands (one at $\sim 5 \mu\text{m}$ and the other at $\sim 20 \mu\text{m}$) which do not fall in the 8-12 μm range (Table 1). The relative characteristics of these materials are discussed below.

3.1 Optical Properties

Refractive indices and transmission ranges of the various materials discussed above are presented in Table 1. Transmission of 1 mm thick samples of *ZnS*, *ZnSe*, *GaAs*, *Ge*, *45CaS*, *55La₂S₃* and a 2 mm thick type-IIa gem diamond at indicated

Table 1. Optical properties of some IR transmitting materials (8-12 μm)

Material	Transmission range (μm)	Absorption coefficient (cm^{-1}) at					Refractive index (10 μm)	dn/dt ($^{\circ}\text{C}^{-1}$)
		3.33 (μm)	5.0 (μm)	8.3 (μm)	10 (μm)	12 (μm)		
<i>Ge</i>	1.8-15			0.02	0.03	0.2 (25 $^{\circ}\text{C}$)	4.0032	27×10^{-5}
			0.17	0.58	0.66	0.94 (100 $^{\circ}\text{C}$)		
<i>GaAs</i>	1.8-16	< 0.01	< 0.01	< 0.01	< 0.01	0.09 (25 $^{\circ}\text{C}$)	3.2769	-
			< 0.01	< 0.08	0.15	0.42 (400 $^{\circ}\text{C}$)		
<i>ZnS</i> (CVD)	1-12	0.02	0.02	0.08	0.08	- (25 $^{\circ}\text{C}$)	2.2002	4.33×10^{-5} (10 μm)
			0.02	0.15	0.15	- (600 $^{\circ}\text{C}$)		
<i>ZnSe</i> (CVD)	0.6-22	< 0.01	< 0.01	< 0.01	< 0.01	- (25 $^{\circ}\text{C}$)	2.4070	6.1×10^{-5} (10 μm)
			< 0.01	< 0.01	< 0.01	- (600 $^{\circ}\text{C}$)		
42.5 <i>CaS</i> - 57.5 <i>La₂S₃</i>	2-15			0.2	0.17	0.5	~ 2.53	
				(App. Abs. Coeff.)				
Diamond with 2 absorption bands at $\sim 5 \mu\text{m}$ and $\sim 20 \mu\text{m}$ (synthetic 2 mm thick layer)	0.3 to $>100 \mu\text{m}$	1	12	< 0.03	< 0.03	< 0.03 (25 $^{\circ}\text{C}$)	~ 2.38	
		2.5	18	< 0.03	< 0.03	< 0.03 (600 $^{\circ}\text{C}$)		

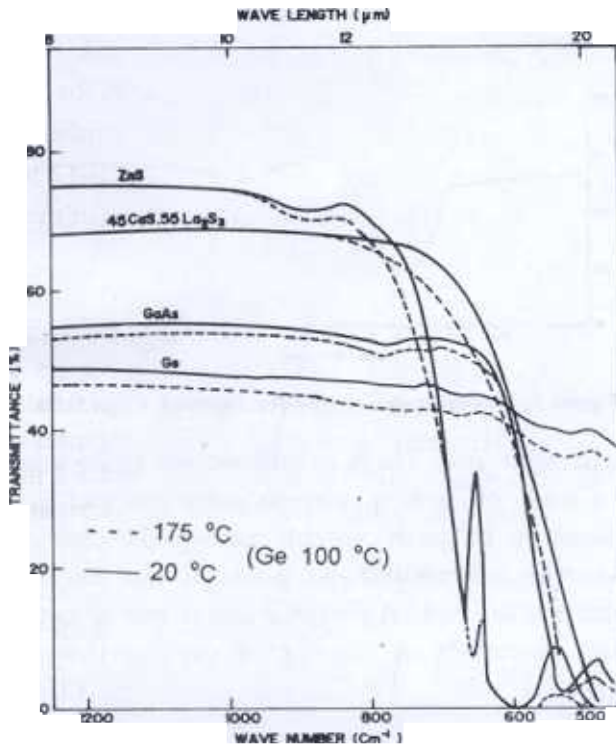


Figure 1. Transmittance of 1 mm thick samples of *ZnS*, *GaAs*, *Ge* and *45 CaS. 55 La₂S₃*.

temperatures are shown in Figs 1-3. Though *Ge* shows good transmission up to $\sim 12 \mu\text{m}$ with slow decline in the transmission behaviour up to $20 \mu\text{m}$, free electron absorption restricts its use only up to $70 \text{ }^\circ\text{C}$ and hence, it cannot be used in such applications where major aerodynamic heating is involved. *GaAs* shows good transmission up to $16 \mu\text{m}$, but its use is also restricted up to $200 \text{ }^\circ\text{C}$. *ZnS* though suitable at higher temperatures because of its larger energy gap, has got a relatively shorter transmission range with its transmission being useful up to $12 \mu\text{m}$. CVD *ZnS* shows better transmission behaviour than hot pressed samples and the former can be further improved through a post-deposition treatment; the resulting body is known as 'Cleartran' *ZnS*¹⁶.

Xue and Raj¹⁰ investigated the role of hot pressing conditions on the optical transmission of *ZnS* and concluded that grain size and phase composition play key roles.

CaLa₂S₄ shows slightly lower transmission than *ZnS*, but its range is relatively longer. *ZnSe* shows maximum transmission among the existing

Table 2. Mechanical and thermal properties of some IR transmitting materials (8-12 μm)

Property	<i>Ge</i>	<i>GaAs</i>	<i>ZnS</i>	<i>ZnSe</i>	<i>42.5CaS</i> <i>-57.5La₂S₃</i>	Diamond
Density ($\text{kgm}^{-3} \times 10^3$)	5.32	5.32	4.08	5.27	4.26	3.515
Hardness (GPa)	8.3	7.4	2.2	1.0	5.6	88
Young's modulus (GPa)	103	85	75	70	96	1050
Fracture toughness ($\text{MNm}^{-3/2}$)	0.6	-	0.65	0.7	0.53	-
2 mm water drop damage threshold velocity (m/s)	205	-	170	137-152	250	-
Thermal expansion coefficient $\times 10^{-6}/^\circ\text{C}$	6.1	5.7	7.4	7.57	14.7	0.8
R'	8.0	3.7	2.1	1.4	0.7	5604
Thermal conductivity (W/mK)	70	35	17	18	1.7	2000
Poisson ratio	0.279	0.28	0.29	0.28	0.25	-0.2

materials, its range extending up to $18 \mu\text{m}$ even for thicker windows (thickness $\sim 14 \text{ mm}$). Temperature-degradation of transmission is also least in the case of *ZnSe*. As *ZnSe* is mechanically weak, *ZnS/ZnSe* composite windows have been fabricated. A typical transmission curve for (6 mm *ZnSe* + 1 mm *ZnS*) window is shown in Fig. 2. Transmission behaviour of diamond shows that it is the best material for use in 8-12 μm range.

3.2 Mechanical Properties

Various mechanical properties of some IR transmitting materials are given in Table 2. It is apparent that most of the mechanical properties of the emerging material, *CaLa₂S₄*, are either superior to those of *ZnS* or approach them. Particularly significant is the threshold velocity for damage by

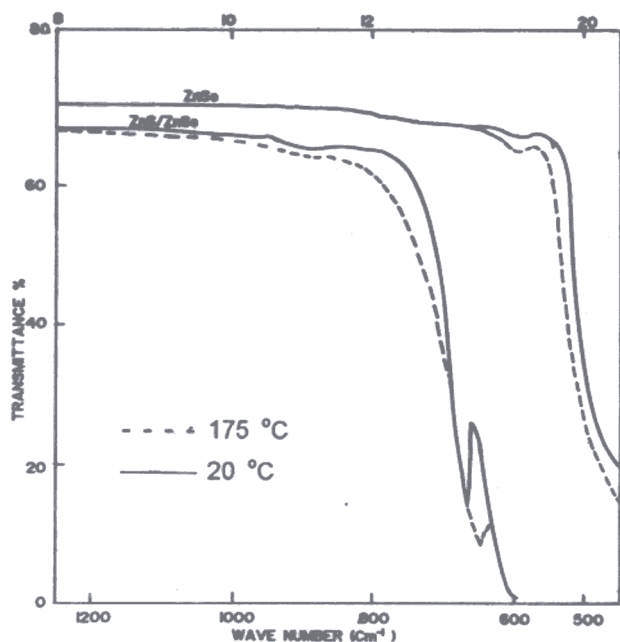


Figure 2. Transmittance of 1 mm thick sample of *ZnSe* and (1 mm *ZnS* + 6 mm *ZnSe*) laminate.

rain drops. *Ge* and *GaAs* are mechanically superior to *ZnS*, but their temperature range is limited, leaving the competition between *ZnS* and *CaLa₂S₄*. Diamond, of course, is a much superior material when mechanical properties are the criteria.

3.3 Thermal Properties

During high speed flights, the window materials become hot, and their optical properties are likely to be impaired. *Ge* and *GaAs*, with low energy gaps, develop the capacity for increased absorption of radiation due to increased free electron generation. *ZnS* is better and *ZnSe* is still more useful in this regard. Materials should be thermal shock resistant. A thermal shock figure of merit²⁹ has been defined as:

$$R' = \sigma k (1-\nu) / a E$$

where σ is fracture strength; ν , Poisson's ratio; k , thermal conductivity; a , thermal expansion; and E , the Young's modulus. R' values of the materials are listed in Table 2. It is observed that *Ge* and *GaAs* have better R' values than *ZnS* which is superior to *ZnSe* and *CaLa₂S₄*⁶. The last named is not at all useful for windows which experience a sudden

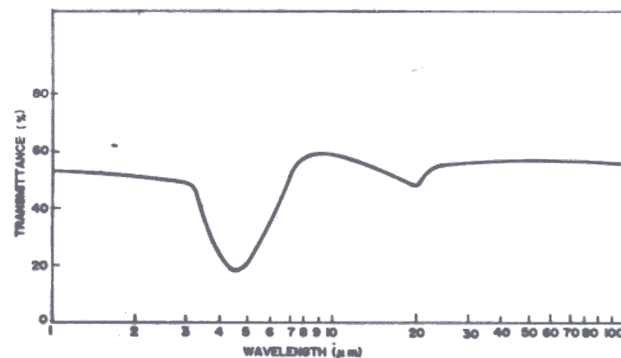


Figure 3. Transmittance of type IIa diamond, 2 mm thick

temperature rise. These considerations again point to a trade-off among various materials and *ZnS* appears to be most suitable among the existing materials. Diamond, as pointed out earlier, possesses the highest potential and is way ahead of other materials in respect of various thermal properties.

4. CONCLUSION

Electrooptic systems, the platforms they perform on, and their missions, continue to place increasing requirements on IR domes and windows associated with them. Thus, more and more robust, optically transparent and thermally stable materials are required. The materials currently available for these requirements, such as *Ge*, *GaAs*, *ZnS*, *ZnSe*, emerging materials like *CaLa₂S₄* and the most ideal material, diamond, are discussed in the light of these requirements. Methods for their synthesis and their characteristics have been reviewed.

It appears that other than diamond, no other material is suitable for all applications. Up to 100 °C, *Ge* is quite suitable. For window applications up to 200 °C, *GaAs* is quite good, whereas for window temperatures higher than 200 °C, there is close competition between *ZnS*, *ZnS/ZnSe* laminates and *CaLa₂S₄*. Depending upon the requirement, some characteristic may be traded-off for some other and choice of the material made accordingly. Diamond is the ideal material for these applications. Recent developments in the field of synthetic diamonds have been discussed.

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REFERENCES

- 1 Donald, W. & McMillan, P.W. Infrared transmitting materials. Part I. Crystalline materials; Part II. Non-crystalline materials. *J. Mat. Sci.*, 1978, **13**, 1157-76. & 2301-12.
- 2 Leverenz, H.W. An introduction to luminescence of solids. John Wiley and Sons, London, 1950. pp. 473-75.
Nakano, E. Degree of crystallinity of Zinc Sulphide precipitated from homogenous solution. *Kogyo Kagaku Zasshi*, 1968, **71**, 304-305.
- 4 Celikkaya, A. & Akinc, M., Preparation and mechanism of formation of spherical submicronmeter Zinc Sulphide powders. *J. Am. Ceram. Soc.* 1990, **73**(8), 2360- 65.
- 5 Akinc, M. & Celikkaya, A., Synthesis of ZnS. powdres. *Proceedings of SPIE*, 1989, **1112**, 60-7
- 6 Berak, J. & Beran, T., Synthesis of ZnS. *Zesz. Nauk. Politech. Slask. Chem.*, 1979, **88**, 153.
- 7 Carnall, E. (Jr). Hot pressing of ZnS and CdTe. *J. Am. Ceram. Soc.*, 1972, **55** (11), 582-83.
- 8 Uematsu, K.; Sawada, K.; Kato, Z.; Uchida, N. & Saito, K., Effect of additives on the hot pressing of Zinc Sulphide, *J. Mat. Sci. Lett.*, 1988, **7**, 473-74.
- 9 Huffadine, J.B.; Whitehead, A.J.& Latimer, M.J. A single hot isostatic pressing technique. *Proc. Brit. Ceram. Soc.*, 1969, **12** 1201-209.
- 10 Xue, L.A. & Raj, R. Effect of hot pressing temperature on the optical transmission of Zinc Sulphide. *Appl. Phys. Lett.*, 1991, **58** (5), 441-43.
- 11 Pappis, J., Miles, P.A. & Donadio, R. Proceedings of the second conference on IR laser window materials, 1972. AFCRL-TR-73-73072 II 737-50 (1973).
- 12 Savage, J. A.; Lewis, K.L.; Pitt, A. M. & Whitehouse, R.H.L. The role of a CVD research reactor in studies of the growth and physical properties of ZnS infrared optical material. *Proceedings of SPIE*, 1984, **505**, 47-51.
- 13 Taylor, R.C., & Corn, J.B. Metallic sulphides and tellurides USA Patent., 3, 390, 090. June 25, 1968, 4p.
- 14 Korczynski, A. Preparation of heavy metal selenides in aqueous solutions. *Chem. Stosow.* 1981, **25** (3), 391-99.
- 15 Kenzo, M. & Takeyo, A. Fine pure ZnSe. Japenese Patent, **6**, 137, 808. 22 July 1985, 2p.
- 16 Taylor, R.L. & Donaldio, R.N. An infrared alternative: Vapour deposited materials, *Laser Focus*, 1981, 41-43.
- 17 Halfner, H.C & Braun, M.J. Development of GaAs for IR windows. June 1976. Final Tech. Report No. AF-33615-75-C-5274.
- 18 Klocek, P. & Weirauch, D.F. Pressure sintering of III-V compounds. *Proceedings of SPIE*, 1989 **1112**, 105-18
- 19 White, W.B.; Chess, D.; Chess C.A. & Biggers, J.V. $CaLa_2 S_4$, Ceramic window material for the 8-14 μm region. *Proceedings of SPIE*. 1981, **297**, 38-43.
- 20 Covino, J.; Harris D.C.; Hills, M.E.; Loda, R.T & Schwantz, R.W. Development of $CaLa_2 S_4$ as an 8-12 μm transmitting ceramic. *Proceedings of SPIE*, 1984. **505**, 42-46.
- 21 Diamond as IR window material in pioneer venus infrared radiometer, *Int. Diam. Rev.* 1979, **39**, 115-17.
- 22 Bundy, F.P.; Strong, H.M. & Wentorf, R.H. (Jr). Methods and mechanisms of synthetic diamond growth. *Chem. Phys. Carbon*, 1973, **10**, 213-63.
- 23 Komo, M.; Sato, Y.; Matsumoto, S. & Setaka, N.; Diamond synthesis from gas phase microwave plasma. *J.Cryst. Growth*, 1983, **62**, 642-44.
- 24 Kobashi, K.; Nishinmura, K.; Kawate, Y. & Horiuchi, T. Synthesis of diamonds by use of microwave plasma chemical vapour deposition

- morphology and growth of diamond films. *Physics Review. B*, 1988, **38** (6), 4067-84.
25. Matsumoto, S.; Sato, Y.; Tsutsumi, M & Setaka, M. Growth of diamond particles from methane-hydrogen gas. *J. Mat. Sci.*, 1982, **17**, 3106-112.
 26. Setaka, N. Low pressure gas phase synthesis of diamonds. *Hyomen (Surface)*, 1984, **22**, 110-17. (Japanese.)
 27. Ravi, K.V.; Koch, C.A.; Olson, D.S.; Choong, P.; Vandersande, J.W. & Zoltan, L.D. Electrical conductivity of combustion flame synthesised diamond. *Appl. Phys. Lett.*, 1994, **64**, 2229-231.
 28. Harris, D.C. Properties of diamond for window and dome applications, *Proceedings of SPIE*, 1994, **2286**, 218-28.
 29. Richerson, D.W. Modern ceramic engineering. Properties, processing and use in design. Marcel Dekker, Inc., New York, 1982. p.140.

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