PROPERTIES AND OPTICAL WORKING OF INFRARED MATERIALS

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Optical and physical properties of various infrared materials of current interest are reviewed and the criteria for selecting suitable materials for specific purposes along with the factors affecting the performance of IR components under different conditions of use are discussed. The techniques of optical working of different infrared materials viz., cutting, grinding, polishing, protective coating and testing are also described in detail.

While selecting materials for infrared optics, the anisotropy of optical constants and the mechanical and chemical properties of substances have also to be considered in addition to their transmission characteristics. This requires different materials for different IR spectral ranges and also restricts their use for specific purposes, for example, excellent optical properties may have to be sacrificed for field applications if the material is not resistant to sudden changes in pressure and temperature or is affected by moisture when exposed to atmosphere. This paper discusses the criteria for selecting suitable material for specific purposes and describes the properties and the techniques of optical working of various IR materials.

CHOICE OF MATERIALS

The difference between the optical working of glass and IR materials lies in the latter's softness, anisotropy, transmission, refractive index, plastic deformation, brittleness, and resistance to water and acids. Glass is available in comparatively large sizes and is a relatively cheap material. Being hard, it is less liable to sleeks and scratches. Although it is sensitive to temperature changes, it is little affected by humidity, acids, alkalies and other chemicals. It is rather unaffected by changes in pressure. Therefore, the techniques of optical glass working are much the same for all types of glasses. Infrared materials, on the other hand, are costly and are available in relatively small sizes only. They are soft (except for a few crystals like KRS-5) and are attacked by humidity, acids, alkalies and other chemicals to different extents. Hence the technique of their optical working differs from crystal to crystal[1]. Crystals may distort under pressure and begin to cleave under thermal and mechanical shock. Stress patterns appear during cleaving of the crystal and scratch free surface is difficult to obtain. In the case of semi-conductors, the impurities not only give rise to their own absorption bands but also produce free carriers with increasing temperature thereby increasing the reflectivity. Therefore, the purity of the materials is one of the important factors in the design of IR components. Protective and anti-reflection coatings can be made on glass surfaces, but most of the crystalline substrates used in the IR range with the coating material, *e.g.*, SiO, is also changed to SiO_2 on sodium chloride surfaces which is corrosive to most metals. All kinds of glasses transmit the visible part of spectrum, but different IR materials are required for different wave length regions of the vast infrared spectral range. Thus, different anti-reflection coatings have to be used with different IR materials and a compromise must be made between high refractive index and the narrow wave length band produced by the anti-reflection coating.

In the case of lenses the high-refractive index of infrared materials may give higher dispersion, but the resolution is reduced due to higher aberration. Also, the re-radiation from the optical components heated by the infrared radiation could produce a false image. However, aberration-free systems can be fabricated with the wide range of IR materials available. Birefringence is another problem posed by the material; the faults and stress in the crystal will then give rise to distortion of image in different planes[2]. This can be overcome by making the optical axis of crystal coincident with the optical axis of the lens and parallel to the base of the prism. The effect of optical rotation can be eliminated by cementing together two levo-and dextro-rotatory prisms each with half the apex angle required. Hence the material for a particular wave length region has to be selected by considering not only the homogeniety and isotropy of optical properties, but also mechanical, thermal and chemical properties. Table 1 summarizes the relevent properties of materials[3—23] commonly used in infrared optics. Thermoplastics such as nitrocellulose, PVC, perspex, polystyrene, polyethylene, teflon, ethyl cellulose etc. can also be used as optical components. These are resistant to mechanical and thermal shocks, and are not attacked by acids and alkalies. However, these are soft materials and become softer at not too high temperatures. Also the multiplicity of their absorption bands in infrared region and the increased absorption and widening of the absorption bands for thicker samples restricts their use in optical components.

MATERIALS FOR SPECIFIC PURPOSES

For optical windows, the materials should have high transmission, low dispersion, low refractive index, low coefficient of thermal expansion, low water solubility and high hardness. The window material should also have a high melting point and resistance to solarization. Fused quartz, alkali halides, $AgCl$, MgO, Al_2O_3, KRS-5 and diamond are some of the materials used for making windows. For absorption cell windows, the cold flow and the resistance to chemicals is an important factor, while for field use, resistance to sudden changes in temperature, large pressure gradients and the abrasion by wind-carried particles is also to be considered. IR domes are preferred for use in fast moving objects like missiles where the large temperature changes due to aerodynamic skin heating and the resulting differential thermal expansion of the two surfaces are the determining factors. Windows for use upto the far infrared region can be fabricated from alkali halides but these are hygroscopic. Silver chloride can be made resistant to moisture and solarization by coating it with silver sulphide or stibnite[24] but it is a rather soft material for such purposes. KRS-5 is not always homogeneous; it is soft and toxic and exhibits cold flow which spoils the figure of the optical surface with time. Germanium and silicon can also be used as windows. In the intermediate range (3-8 μ m) plates and segmented domes of MgO, As_2S_3, Kel-F (polytetrafluorochloroethylene), rutile (TiO_2), Sapphire (Al_2O_3) and arsenic modified selenium glasses[25] are used in addition to the above materials. From the visible to the near infrared region, fused silica can be used advantageously for all kinds of optical components.

Materials suitable for making prisms must have the desired transmission and refractive index. The gradient of refractive index as found in KRS-5 is undesirable. Normally a material having high dispersion is chosen although too high a dispersion has to be sacrificed for the sake of resolution to reduce aberration. Suitable optical materials for fabricating prisms for use in different wave length regions are quartz, LiF, KI, CaF_2, $NaCl$, KBr, KRS-5, $CsBr$ and CsI. The inhomogeniety in mixed crystals like KRS-5 has a perfoundly adverse effect on the performance of prisms and results from the unawareness of accurate melting point and also from the deformations and strains introduced during cutting and grinding of such crystals. Such prisms, if not annealed properly, will show broad spectral lines and even *ghost lines*. Water solubility and thermal properties of prism materials are not so important factors as these are used in controlled atmosphere.

The use of lenses in infrared optics is generally avoided although materials like LiF, CaF_2, KBr, Si and Ge have been used for various combination of lenses. Quartz-LiF, quartz-florite and quartz-LiF-quartz combinations[26] have been used in the range 0.185-14 μ m. Usually spaced doublets are used whenever desired. Alkali halide components, being isotropic, do not affect the transmission of light in different directions. The effect, however, is pronounced in crystals[27] like quartz, calcite, and $NaNO_3$.

Apart from the transmission characteristics in the near and far infrared regions, IR filters have also been designed on the principle of absorption, refraction, reflection, scattering and interference of light [28-30]. Alkali halide crystals, strongly coloured with metal vapours like potassium, cut off visible light and their ultra-violet absorption edge can be shifted by doping with a suitable concentration of impurities[31] like Tl, Pb, Ag or Cu. Interference-polarization filters for norrow spectral ranges can be fabricated by a set of birefringent crystal plates having their thickness in a geometrical progression and laminated by polarizers[31,32]. Quartz and calcite are widely used in polarising optics. For the intermediate and far infrared regions, however, a set of plane parallel plates of a highly reflective crystal like $AgCl$, kept at the polarising angle, is used. Only five films of selenium, each 4 μ m, thick are needed to produce more than 95 per cent polarization in the transmitted beam between 2-14 μ m. Polarizing materials of high refractive index need large angle of incidence and make the unit bulky. For wave lengths greater than 15 μ m, multiple sheets of polyethylene may be used. Polarization can also be obtained by reflection from one or more films or silicon or germanium evaporated on to a glass substrate.

TECHNIQUES OF FABRICATION

Cutting and Grinding

Whenever possible, cleavage is the best method of preparing flat surface although the dislocations increase in the region of cleavage[33]. Cleaving can be done by exerting a small pressure on the crystal edge by means of a sharp instrument or by giving a thermal shock at a point. Cubic crystals like alkali halides cleave easily, but good cleavage in large crystals is difficult to obtain. Crystals like $CsCl$, $CsBr$, CsI, $AgCl$ and KRS-5 are too soft, while germanium and silicon are too brittle for cleavage. In such cases, therefore,

cutting is done by thread, band saw, or diamond saw, depending upon the hardness of the material. Soft crystals are cut by a thin taut linen fibre impregnated with a suitable abrasive ; $NaCl$, KCl, and KBr can be cut even by ordinary plastic thread or steel wire moistened with water or with abrasive mixed in kerosene. Fluorides should be cut with copper blades [34]. Band saw can be used for cutting crystals of medium hardness, while Germanium, Silicon and Sapphire are cut with a diamond impregnated wheel. Proper orientation of the cutting direction is important as the local heating during cutting may produce surface cracks or tearing. Thin slices, upto a few micrometers thick, can also be cut by stream etching in which an etchant is flown along a vertically stretched thin wire which also forms a cathode with respect to the crystal being cut[35].

Specimen of cylindrical shape can be cut by a sharp edged brass tube fitted to a vertical rotating shaft. The peripheral speed should be kept nearly 50 ft/min, but this depends upon the mechanical strength[36] of the crystal. Cleavage may occur at high speeds of revolution or under large pressure from the tool. The hollow portion cut by the tool should be filled with abrasive and some oil. Wax cement prepared by boiling wax and resin together can be used to fix the blank on the glass plate. The above procedure holds for drilling holes too. Care should be taken to prevent the chipping of the edges of the hole. Drilling for small intervals of time and frequent use of a new abrasive is desirable. Generally, a hand drill machine is found more suitable for drilling holes.

Plastic deformation-free machining of crystals can be accomplished by gently feeding the rotating water cooled specimen into a chemical drill[37]. The etchant is fed through the inner tube of a double walled glass capillary tube which has an etched bulb-shaped tip which helps to distribute the chemical uniformly over the contact area. The etchant is sucked into the outer tube through the groove in the tip. Chemical removal at the tip is most effective when the drilling is done horizontally. In the vertical orientation excessive chemical will accumulate in the region near the tip and produce large irregularly shaped holes. A typical rate of drilling is $0\cdot3$ inch per hour while rotating the crystal at 50 r.p.m.

In the grinding and smoothing processes for giving rough shape to crystal surfaces, we have to take into consideration the harness and the solubility of these materials. The abrasives must be chosen according to the hardness of the piece to be worked. The abrasive must bite without penetrating deeply into the solid. The most-biting abrasives can be used only with very hard substances. Bigger abrasive particles sizes may result in cracks or chipping of the surface. Also, the pressure has to be regulated in relation to the hardness of the material. Some of the plastic materials, like $AgCl$, can even be turned on a lathe. Mechanical grinding or polishing introduces surface lattice distortion which may extend to a depth of several micrometers (upto twice the diameter of the grinding or polishing particles[38]) below the surface, depending upon the hardness of the crystal and the pressure and the duration of optical working. Hence, the change in the crystalline structure at the surface will depend upon the nature of the crystal and the working conditions. In soft materials like KRS-5, grinding produces flow lines[39] which cannot be detected until polished. These lines, a few tenths of a micrometer deep, appear on the surface after a few days and depend upon the grain size of the abrasive and the pressure applied during grinding. However, annealing at 200°C for twenty-four hours makes it possible to produce a flow-line-free optical surface. To get rid of chipping, all corners and edges should be well bevelled. It is advantageous to produce an accurate ground surface, as it is difficult to rectify faults during polishing. While grinding, the surface can be tested in the reflected light at large angles of incidence [40]. Usually, putty powder, chromium oxide, Linde A powder, cerium oxide, red rouge (Fe_2O_3) and white rouge (titanium dioxide) are used for grinding and polishing of materials [41,42]. Very soft crystals like calcium carbonate are ground with SnO_2, while Cr_2O_3 is used for crystals like fluospar, aragonite, $NaCl$ and KCl. Rouge is especially effective on hard substances, while ruby has to be ground with natural quartz powder. Grinding with an abrasive of mesh size 120-300 for twenty minutes should be followed by polishing with the particle size down to 1 or $0\cdot5\mu$m. Care should be taken to clean the tools properly after use as many of the infrared materials are corrosive. The use of brass tools and glass plates is recommended.

Polishing

Crystal surfaces are more difficult to polish than glass. They also require careful sealing and storage in a dry place. Cleaved surfaces, though clean, shining, and more resistant to fogging by water vapours, are not as optically flat as desired for precision optical measurements. Mechanical polishing, with a pitch lap and rouge or any other abrasive, produces accurate surfaces but care has to be taken to avoid sleeks and scratches. Chemical polishing using acids and other etchants gives a good polish but does not give the flatness of surface[43]. Many workers have used water to speed up the grinding and polishing by using materials like alkali halides. Pitch lap with a saturated salt solution with no abrasive, can also be used for $NaCl$ but

the surface gets tarnished with time. The finishing is done on a barely moistened lap just about to dry. Glass plates with breath wetness can also polish optical surfaces to a few fringes. This method avoids polishing material being embedded deep into the crystal surface. However, the authors' experience is that the use of water at any stage tends to create cleavage planes especially near the edges of the specimen and also causes instability in the optical surface. Thus even the moisture from the breath is to be avoided. Kerosene oil or automobile oil is found very suitable. Alcohol evaporates rapidly and leaves the abrasive dry.

The quality of the surface produced is governed by its hardness and type of lap used[44,45], type of strokes[46,47], dust-free, humidity-free and temperature-controlled atmosphere etc. After grindig with a very fine grade abrasive in some suitable vehicle like ethyl alcohol, the surface can be polished with the same abrasive on a well-pressed and stretched lintless swabbed velvet or silk cloth. Only five minutes of such polishing produces a surface which is good enough for infrared work.

The authors have also found the following composition very suitable for producing stain-free and scratch-free surfaces. Dry pitch is doubly refined and mixed with 1/5 parts of resin and filtered through a fine cloth. Turpentine oil is then added to the molten mixture till its hardness is somewhat lower than that of the crystal. It is then thoroughly mixed with about 15% of beeswax and about 10 grams of rouge (red or white). Paraffin wax is found better for polishing LiF. Care should be taken that Fe_2O_3 or TiO_2 does not get embedded in the surface of the material as their absorption bands lie in the infrared region[48]. No abrasive should ever be allowed to dry up on a surface. Instead the surface should immediately be cleaned by a dry cloth. Rouge particles left on the surface catch moisture from the atmosphere and produce circular etch pits. The abrasive particles can be removed with a cloth dampened with methanol, ethyl alcohol, CCl_4 or acetone. The moist polished surface should be dried by rubbing on a well-pressed and stretched dry cotton swabed cloth. We have found that the surfaces produced by this method are good and are less affected by moisture. The pitch lap must be kept clean and preserved by pressing against another flat glass or steel plate.

$KRS-5$ can be polished with SnO_2 on a cloth or even by polishing with the residue left over by the evaporation of the household window cleaning agents[49]. The coarse particles may be mixed in the pitch lap while the finer ones can be used with water. Al_2O_3 with soap cream and water also produces good surfaces. Cesium halides can be successively polished on pure silk or pure cotton velveteen stretched on a flat glass plate[60] or by using successively finer grades of Al_2O_3 on a moist rayon cloth. Germanium and silicon can be easily polished with the pitch lap together with rouge or Al_2O_3 paste.

Chemical polishing by etchants is another method of obtaining good surfaces. However, care must be taken to ensure that the chemicals used do not give any preferential etching in different crystal directions as the optical surfaces are likely to contain many crystallographic planes. The rate of etching can be controlled by diluting the strength of the etchant and also by lowering the temperature. Table 2 gives the various etchants[51-60] used for different materials.

Protective Coating

Having prepared the optical surface as above, it is found that the quality of the polished surface deteriorates with time either due to the strains produced in the crystal during grinding and polishing or when it is left open to the atmosphere. The effect of strains can be removed by heating the component at about 200°C below its softening point for a period of four hours and then slowly cooling it down. Any minute cracks present in the surface seal up at such high temperatures due to flow of the material. Recrystallization may occur at the surface due to contact with chemicals or due to temperature changes[61]. This outer layer is also more resistant to moisture. However, it is sometimes found that a white residue appears at the surface after annealing. This may be removed by rubbing on a dry cloth with methanol. To facilitate handling, the top and bottom of the IR components should be covered with glass plates. However, to protect the surface from atmosphere, the hygroscopic optical components should be enclosed in a chamber containing silica jel or maintained at a temperature somewhat higher than the ambient temperature. Alternatively, the surface may be coated with some suitable film material depending upon the type of application. The coatings not only protect the surface from moisture, chemicals, solarization, oxidation and mechanical damage, but also reduce the reflection losses in the case of refracting elements and increase reflection in the case of mirrors. It is sometimes found that even if the coating material itself is not affected by water, the moisture weakens the bond between the coated layer and the substrate thereby destroying the coating. Also, for larger thicknesses, the mechanical stress produced in the evaporated film may exceed the adhesion of the film to the substrate thereby chipping it off the surface. MgF_2 and cryolite (Na_3AlF_6) have considerably higher mechanical stress than SiO and hence can be used in very thin coatings ($< 5\ \mu m$) only. Platinum and rhodium also

form protective coatings and these are not reacted upon by the IR materials; rhodium is somewhat better than platinum in transmission characteristics. Germanium is also a good and hard film material for 15 μ m and beyond, despite slight absorption in this region. Some of the common filming materials [62—63] are given in Table 3.

An *NaCl* surface can be also be protected by dipping it in a very dilute solution of asphaltum dissolved in water-free xylene[64]. This gives an excellent coating without affecting the transmission characteristics. The refracting surfaces can also be coated with a thin film of pyroxylene dissolved in amylacetate[65]. Coatings obtained by dipping in a dilute solution of polystyrene or polyethylene are also used. Fluropolymers [66] also protect the components during polishing. After drying for 10 to 20 minutes at room temperature, it is heated upto 80 to 90°C in the oven. The coating is stable upto 200°C.

For protection of hygroscopic surfaces, annealing is not sufficient although due to recrystallisation of surfaces, it is stable to some extent whereas coating with material other than base material affects transmission and other optical properties. The most promising approach seems to be conversion of surface layer into a non-hygroscopic layer [67]. One of the ions of the base material may be replaced by exchange reaction to another stable, non-hygroscopic compound. The thin layer does not affect the optical properties of the material in various optical regions. Silica wax and cathode sputtering of organic coatings are also used to protect the materials. Nitrocellulose, polyvinyl chloride, methylmethacrylate[68], polystyrene, polyethylene, polytetrafluoroethylene, and ethylcellulose are some of the thermoplastics used for coating against phenolformaldehyde, polyvinyl fluoride, formaldehyde, alkyd, polyester resins etc. which are not so much used. Epoxy resin (Epichlorohydrin + polyhydric alcohol) produces a good adhesive film. Cellulose acetate, polyvinyl acetate, methyl methacrylate, polycyclohexylmethacrylate, polystyrene etc. are also used in precision optical components. These materials can be machined without danger of fracture and are lighter, more resistant to mechanical and thermal shock, acids and alkalis; though stable these are softer than glass and soften at lower temperatures.

Thermally stable films are made from phenyl polysiloxanes or organosilicon resin by putting small amount of solution on to the rotating component[69]. Evaporation of the solvent leaves uniform polymer film, giving better adhesion and good antireflection coating. Curing at 300°C for 3 to 5 hours achieves complete solvent removal and cross linking. Phenyl methylsiloxane films are transparent to visible and IR. They do not absorb below a thickness of $7 \cdot 5$ μ m the absorption bands lie between 7 and 10 μm. Fluoropolymer films become stable after heat treatment and can be removed later on, mechanically.

Stibnite or silver sulphide films can protect *AgCl* from solarization. PbF_2 and *ZnS* provide good antireflection coatings [47] for high refractive index materials like germanium or silicon. It is found that a condensed layer of *SiO* gradually changes to SiO_2 in air, giving a milky appearance to the surface [45,47]. *MgO* films are resistant to corrosion, abrasion and scratches while sublimed films of selenium are very reflective [7,24].

Aluminium is the only coating material which has high reflectance in the ultra-violet, visible and infrared regions. Platinum is good for the vacuum ultra violet, while *Ag* and *Cu* reflect more than $98 \cdot 5\%$ of the incident radiation in the infrared region. However, these tarnish easily, and aluminium is most frequently used as it is also easy to evaporate and has good adherence to substrates[63]. Although MgF_2 is used for protecting aluminium films in the vacuum ultra-violet, *SiO*, quartz, or strongly oxidized films of *SiO* are used in the near ultra-violet and visible regions. The strong absorption band of SiO_2 near 10 μm has little effect on the reflectance of mirrors when coated in very thin films of the order of $0 \cdot 15$ μm, thick i.e. films thinner than the wave length of the radiation used. This is true for all absorbing materials like water or grease. Because of the above reasons, it is evident that refracting surfaces must be cleaned more frequently than mirrors. Suitable coating for common IR materials are given in Table 4.

Testing

The testing methods of optical surfaces for use in the infrared region are the same as for the visible region[70]. In fact, the tolerance in the accuracy of the surface is much greater at longer wave lengths. The flatness of the surface can be determined by the usual interferometric methods. Although the use of lenses in infrared optics is rather avoided, interferometric tests with a pair of curved test plates suffice for controlling the curvature and for determining the magnitude of *hills* or *valleys*. If the IR optical material is transparent also in the visible region, the stress pattern can be determined by a polariscope. The centering of the IR lens surfaces is difficult in case of materials opaque to visible radiation since two visible reflection images[45] from the two surfaces cannot be obtained. The authors have found that the problem may be overcome by making the edges of the lenses of uniform thickness during grinding and polishing. The use of cements[71] for lens systems in IR optics is not possible due to stringent spectral characteristic requirements.

TABLE 1

OPTICAL MATERIALS AND THEIR PROPERTIES

Material	Transmission limit	Refractive Index at		Knoop hardness	Youngs modulus	Melting point	Thermal coefficient of expansion	Thermal conductivity
	(microns)	$(2 \cdot 2\mu)$	$(4 \cdot 3\mu)$		$(10^6$ Psi)	(°C)	$(10^{-6}/°C)$	(cal/sec. cm,°C)
1	2	3		4	5	6	7	8
Optical glasses	2-7	1·5	1·7	300–600	7–10	700	4–10	$1·4-1·8 \times 10^{-3}$
Fused Silica or fused Quartz	4·5	1·43	1·37	470	10·1	1667	0·55	$28·2 \times 10^{-4}$
Silicon	15	3·44	3·42	1150	19	1420	4·2	0·39 (at 20°C)
Germanium	25	4·9	4·02	—	14·9	940	6·1	0·14
Sodium Chloride	15	1·53	1·52	15·2	$4·0 \times 10^{11}$ dyne cm^{-2} (5·8)	801	44 (at 20°C)	155×10^{-4}
Potassium Chloride	0·21–25	—	1·46 (at 10μ)	7·2	4·3	776	36 (at 20°C)	156×10^{-4}
Potassium Bromide	27	—	1·53 (at 10μ)	5·9	3·9	730	41 (at 20°C)	115×10^{-4}
Potassium Iodide	0·2–31	—	1·67 (at 10μ)	5 km/mm^2	$3·15 \times 10^{11}$ dyne cm^{-2}	723	42·6	—
Lithium Fluoride	0·12–7	1·38 (at 2μ)	1·34	99·1 (air grown) 102·1 (vac grown)	11	870	38 (air grown) 36 (vac. grown)	$210–310 \times 10^{-4}$ (air grown) $190–350 \times 10^{-4}$ (vac. grown)
Cesium Iodide	0·24–52	1·75	1·74 (at 10μ)	—	0·8	621	50	27×10^{-4} (at 25°C)
Cesium Bromide	0·2–40	1·66	1·66 (at 10μ)	19·5	2·3	636	48	22×10^{-4}
KRS-5	0·6–38	2·62	2·37 (at 10μ)	40·2	2·3	414·5	58 (at 20°C)	13×10^{-4}

Specific heat	Solubility (g/100 ml of water at 20°C)	Density (g/cm³)	Soluble in	Protection or anti-ref. coating	Crystal structure & colour	Used as	Remarks
9	10	11	12	13	14	15	16
—	0·00	2·3–4·6	HF	SiO, MgF_2	—	—	Can be cut & polished easily, non-toxic, non-hygroscopic.
0·22	0·00	2·20	HF	No necessity	—	Window, dome, lens	Excellent mechanical & thermal properties, non-toxic, isotropic.
0·168 (at 25°C)	0·00	2·33	HF HNO₃ CP₄	Anti-ref. coating of SiO cubic at 4μ ZnS, at long wave lengths $SeO_2 + MgF_2$ $MgF_2 + ZnS$—10μ	Steel gray cubic	Dome, prism	Low dispersion, grinding difficult, can be ground with diamond powder, SiC, Al_2O_3, resistant to corrosion, long wavelength limit depends upon impurity concentration, thickness & temperature. Must be highly polished to reduce scattering losses at the surface.
0·074 (0–100°C)	0·00	5·33	Hot H_2SO_4, Aquaregia	SiO, ZnS (anti-ref.) $PbCl_2$, As_2S^3, Si, $CeO_2 + MgF_2$ Si+didymium fluoride, $ZnS + SiO$.	Cubic	Lens, window, dome	Highest Refractive Index, low dispersion, cut with diamond tool, grinding with diamond powder or SiC or Al_2O_3 finally with 8μ garnet powder, polished on pitchlap fed with Linde A powder, severe absorption at 100°C.
0·204 (at 0°C)	36·0 (at 20°C)	3·16	Water, glycerine, ether, alkali	—	Transparent, cubic	Prism, lens, window	Shaped easily, cheap, cleaves & scratches easily, soft, corrosive hygroscopic due to Mg and Ca
0·162 (at 0°C)	35·5	1·99	-do-	—	-do-	-do-	Soft, hygroscopic, cleaves easily.
0·104 (at 0°C)	65·2 (at 20°C)	2·76	Water, alcohol, ammonia	—	-do-	-do-	Hygroscopic, soft, difficult to polish, scratches easily.
0·75 (at—3°C)	127	3·13	-do-	—	-do-	Prism, window	Very soft, cleaves, very hygroscopic, low reflection losses.
0·373 (at 10°C)	0·26	2·6	Acids	Antimony	-do-	Prism, lens	Hard, cleaves, scratches, easily non-toxic, non-corrosive.
0·048 (at 20°C)	44	4·53	Water	—	-do-	Prism, window filter	Soft, scratches easily, hygroscopic, cleaves, polished on wetc lap.
0·063 (at 20°C)	124·3	4·5	Water, alcohol	—	-do-	-do-	Soft, scratches easily, hygroscopic low reflection losses, low toxicity
—	0·05	7·27	HNO₃, Aquaregia	Amorphous selenium, polyethylene (anti-ref.)	Red cubic	Window, prism	Toxic, no cleavage, scratches & strains easily, non-hygroscopic, cold flow, difficult to polish & isotropic with respect to hardness hence causes difficulty in polishing & curvature, polished on cloth or felt or on soft pitch lap covered with beeswax, with Al_2O_3 & thick cream of soap & water, high reflection loss, can be used in air.

Table 1—contd.

1	2	3	3	4	5	6	7	8
RS-6	0·4–30	2·20	2·18 (at 10μ)	39·5	3·0	424	51 (at 20°C)	$17·1 \times 10^{-4}$
Silver Chloride	30	2·01	2·00	9·5	2·9	458	30 (at 27°C)	$27·5 \times 10^{-4}$
Barium Fluoride	13·5	1·46	1·45	82	8	1280	—	27×10^{-6}
Arsenic Trisulphide	12	2·38	2·35	109	2·3	196	24·6	4×10^{-4}
Indium Antimonide	16	—	3·99 (at 8μ)	—	6·21	523	4·9	$6·4 \times 10^{-4}$
Strontium Titanate	7·0	2·23	2·19	620	—	2080	9·4	—
Rutile	6	—	2·45	880	—	1825	9 ‖ C axis 7 ⊥ C axis	0·0136 (at 43·8°C) 0·0128 (at 83·7°C)
Sapphire	5·5	1·73	1·68	1370	53	2030	5·0 ⊥ C axis 6·7 ‖ C axis	600 ‖ C axis 550 ⊥ C axis
RIR 2	4·7	1·75	—	⁓600	10·2	⁓900	8·3	—
RIR 20	5·5	1·82	1·79	542	12–14	760	9·6	—
RIR 12	5·7	1·62	⌐	594	15·2	⁓900	8·3	—
Irtran 1, Polycryst MgF_2	0·5–9	1·37 (at 2μ)	1·34 (at 4·5μ)	576	16·6 (at 25°C)	1255	11·0	0·026 (at 179°C)
Irtran 2, ZnS	2·07–14·5	2·26 (at 2μ)	2·24 (at 4·5μ)	354	14 (at 25°C)	1830 at 150 psi	6·9	0·026 (at 174°C)
Irtran 3, CaF_2	0·4–11·5	1·42 (at 2μ)	1·40 (at 4·5μ)	200	14·3 (at 25°C)	1360	20·0	0·015 (at 176°C)
Irtran 4, $ZnSe$	0·5–22	2·44 (at 2μ)	2·43 (at 4·5μ)	150	10·3 (at 25°C)	1520	7·7	0·016 (at 422°C)
Irtran 5, MgO	0·4–9·5	1·70 (at 2μ)	1·65 (at 4·5μ)	640	48·2 (at 25°C)	2800	12·0	0·070 (at 168°C)
Irtran 6, $CdTe$	1·5–31	2·71 (at 2μ)	2·68 (at 4·5μ)	45	5·3 (at 25°C)	1090	5·9	0·0065 (at 140°C)

9	10	11	12	13	14	15	16
0·0482 (at 20°C)	0·32	7·2	-do-	-do-	Transparent, cubic	Lens, window	Toxic, non-hygroscopic, cold flow.,
0·0848 (at 0°C)	1·5 ×10·⁵	5·53	NH_4OH, KCN	Ag_2S_3 overcoated with polystyrene or stibniite from solarization, Te, polystyrene	-do-	-do-	Corrosive, toxic, very soft, difficult to polish, scratches easily, non-hygroscopic, darkens by sun-light, slowly in diffused light-remarkable plasticity, can b, turned on lathe, sawn like plastics, hot pressed to any shape photochemical change in UV can be grown in pyrex crucibles
—	0·17	4·89	NH_4Cl water	—	—	—	Soft, non-toxic, slightly hygroscopic.
—	0·00	3·20	Alkali	SiO or thorium oxyfluoride	Red, amorphous	Dome, lens, window	Low thermal conductivity, high coefficient of expansion, susceptible to thermal shock, cut and polished in usual way, non-hygroscopic, non-corrosive, shows cold flow.
—	0·00	5·78	Acetic acid	ZnS, $PbCl_4$ As_2S_3	Cubic	Filter	Soft, brittle, insoluble in water chemically inert.
—	0·00	5·13	—	SiO	-do-	Immersion lens	Polished on lap made up of 50% Tin+50% lead & not on pitch lap or felt, n is approx =5¹ᐟ², ideal for minimizing ref. losses at the front surfaces of some common detector materials.
—	0·00	4·26	Fused Alkali, H_2SO_4	—	Tetragonal	—	Non-hygroscopic, non-toxic, Ref. Index 5¹ᐟ², geometric mean of several common detector materials and air thus minimises reflection losses.
0·18 (at 25°C)	9·8× 10·⁵	3·98	Amm. salts	—	Transparent, hexagonal	Window, dome	Excellent mechanical and thermal properties, non-toxic, extremely hard, must be cut, ground, polished with diamond or boron carbide tools and abrasives, excellent resistance to chemical and weather.
—	0·00	⌐3	—	No necessity	—	—	—
—	—	5·18	1% HNO_3	—	—	—	Good mechanical & optical properties, non-toxic.
—	—	3·07	-do-	—	—	—	-do-
—	Insoluble	3·18	—	No necessity	Polycrystalline, transparent	Window, dome	Hardest of all irtrans, reacts to grinding and polishing, low Refractive Index, emissivity very low even at 800°C, transmits microwave radiations very well.
—	-do-	4·09	Slightly in HNO_3 & H_2SO_4	BaF_2 (anti-ref. coating)	Polycrystalline, translucent, yellow	Dome, lens, window	Readily sealed to glass.
—	Practically insoluble	3·18	—	No effective anti-ref. coating. BaF_2 (anti-ref. coating)	Polycrystalline, hazy white	Dome, lens	Non-toxic, scratches easily, not resistant to thermal and mechanical shock.
—	Insoluble	5·27	—	—	Polycrystalline, transparent	Dome, lens, filter, substrate	Crystal colour brownish yellow.
—	-do-	3·58	Aqueous acids	—	Slightly milky, polycrystalline	Dome, lens, plates	Non-toxic, non-hygroscopic, non corrosive, hard, chemical & weather resistance, surface scum formed in air.
—	-do-	5·85	—	—	Polycrystalline, opaque, black	-do-	Softest of all irtrans, polishing similar to KRS-5, soft wax lap and Linde A powder used for polishing.

TABLE 2

ETCHANTS FOR CHEMICAL POLISHING OF IR MATERIALS

Material	Etchants/polishing agent	Remarks
1	2	3
$NaCl$[51,52]	Glacial acetic acid	Etching time 30 sec.
	Methanol	
	Absolute ethyl alcohol containing an inhibitor of 3 gms of mercuric chloride per litre of alcohol.	
KCl[51,52]	Acetic acid	Rinse with ether, increased contrast and sharpness of pits. Etching time 30–90 sec
	Concentrated solution of poly-vinyl butyrol in buryl or ethyl alcohol. Ethyl alcohol saturated .25% with $BaBr_2$ + 5% methanol containing 100 gm of $BaBr_2$ per litre	
	Propionic acid	Time 30–90 sec. Rinse with ther or petroleum.
KBr[51,53]	As for KCl above; regent grade glacial acetic acid. saturated solution of $PbCl_2$ in ethanol at 50°C. 73% methanol+3% ethanol+22% glycerol+2% ammonia	Rinse with CCl_4, preferential etching observed. Etching time 10–15 sec. Polish attained in 5–10 min.
KI [1,52]	Isopropyl alcohol, pyridine	
LiF[54]	Water; 2×10^{-6} mol fraction solution of FeF_3 in H_2O; water+1.5% ammonia	Dislocation etch pits are formed, etching time 1–2 min.
CsI[55]	Methyl alcohol + glycerol; weak solution of $CuCl_2$ or $FeCl_2$ in methyl alcohol	
$AgCl$[56]	20% butyl amine by volume in ethyl alcohol	Polish with $Na_2S_2O_3.5H_2O$ on wax lap with standard optical techniques.
Fluorite[57]	Saturated solution of di-sodium salt of ethylenediamine-tetracetic acid	Polishing time 15 min.
$NH_4H_2PO_4$[58], $NaClO_3$	Concentrated HCl saturated with cupric oxide 80% +ethyl alcohol 20%+distilled water 20%	—
Ge[57]	$5HF+10HNO_3+11$ acetic acid with 30 mg of I_2 dissolved	Polishing and etching along (100) and (111) directions, time 4 min.
Si[40]	$1HF+3HNO_3$	Polish within 15 sec; small proportion of acetic acid gives faster etch.
BaF_2 & CaF_2[41]	—	Polish with EDTA and alumina (0.3μ) on pitch lap with or without H_2SO_4 or on 50% beeswax+ 50% rosin lap with or without EDTA.
Calcium Aluminate	—	Standard method of pitch lap.
$CaCO_3$[59]	—	Polish with SnO_2 or rouge on cloth.

TABLE 2—contd.

1	2	3
KRS-5	—	Thick soapy suds and water with Al_2O_3; polish with rouge gives maximum transmittance.
$CaWo_4$[59]	Saturated aqueous CrO_3 concentrated HF (2:1 by volume); 2-25 min.	
CaF_2[13]; $Ca_3P_2O_8$[59]	Concentrated tartaric or citric acid at 60–70°C	
Sapphire	—	Polish on tin-lead lap with diamond dust or by oxy-acetyline flame polishing.
Ruby	—	Smoothing on copper tool. Flame polishing or with 1 μ m diamond powder.
Fluospar & Aragonite	—	Grinding and smoothing on brass tool; polish with Cr_2O_3 abrasive.
$SrTiO_3$		Polish with rouge on 50% tin + 50% lead lap.
$BaTiO_3$[59]	0·5% $HF + HNO_3$, 90 sec.	—
As_2S_3	—	Polish with rouge/corundum on iron plate or pitch lap.
Quartz	—	Polish with rouge or diamond powder on pitch lap.
$GaAs$[59,60]	$3H_2SO_4 + 1\ H_2O_2$ by vol; 50°C, 45 minutes. 2·5–20% Br_2 by vol. in methyl alcohol, few tens to 4 minutes	$HNO_3 + H_2O + HF$ in 3:2:1 vol. ratio is chemical polish. Bromine in methanol solution polishes on hard paper; finish with 0·05 μm Al_2O_3 powder or mechanical polish with 1 μ m diamond powder.
Irtran-6 ($CdTe$)	—	Polish with red rouge or Al_2O_3 powder on pitch lap covered with beeswax or on lintless felt.
GaP[60]	Bubble chlorine gas through methyl alcohol with specimen immersed, 5–20 minutes	—

TABLE 3

COMMONLY USED FILMING MATERIALS

Material[22,61,62]	Refractive Index at 6000Å	Spectral region of transparency at λ/4 optical thickness	Evaporation source	Remarks
1	2	3	4	5
Cryolite (Na_3AlF_6)	1·35	0·2–5	Tantalum boat, molybdenum boat	Soft coating.
Magnesium Fluoride	1·38	0.23–5	Molybdenum boat	Hard and durable.

TABLE 3—contd.

1	2	3	4	5
Cerium Fluoride	1·63	0·3–5	Tungsten boat	—
Silicon Monoxide	1·45–1·90	0·35–8	Covered tungsten coil; Mo and Ta heater	Hard and durable.
Titanium Oxide	2·67	0·4–8	Tungsten heater	—
Silicon	3·48*	0·9–8	Induction heating, electric bombardment	Hard and durable.
Thorium Oxyfluoride	1·52	0·2–10	Molybdenum boat	—
Zinc Sulphide	2·32	0·38–14	Howitzer, Molybdenum boat	Hard and durable
Germanium	3·80*	1·4–20	Tantalum boat, tungsten boat	—
Lead Telluride	5·10*	3·9–20	Molybdenum boat	—
Cerium Oxide	2·2	—	Tungsten, tantalum boat	Hard and durable.
Aluminium Oxide (Al_2O_3)	1·62	—	Electric bombardment, tungsten boat	—
Antimony Trioxide	1·85	—	Platinum heater	Soft coating.
Magnesium Oxide	—	—	Molybdenum boat	Abrasion, scratch and corrosion resistant.

*Typical values in the infrared.

TABLE 4

COATINGS FOR COMMON IR MATERIALS

Material [7,16,24,27,41,63]	Coating Material
Optical glass	SiO, MgF_2.
Se glass	Polystyrene.
CsI & CsBr	Polystyrene.
LiF	Sb.
NaCl	MgF_2, SiO, amorphous Se, plastics.
KRS-5	Polyethylene (anti-ref.), amorphous Se.
AgCl	As_2S_3, coated with polystyrene or stibnite for protection from solarization Si, Ge, Te, polystyrene.
Alkali Halides	Thermoplastics (e.g. polymethyl methacrylate, polystyrene, etc.) SiO, MgF_2.
As_2S_3	SiO or thorium oxyfluoride.
$SrTiO_2$	SiO.
CaF_2	Bi, MgO.
Calcium Aluminate	Anti-ref. coating by MgF_2.
Fused Quartz	Blooming with MgF_2; LiF.
Ge	ZnS, MgO, SiO, As_2S_3, $PbCl_2$, $Si + CeO_2 + MgF_2$; $ZnS + SiO$, $Si + didymium$ fluoride, stibnite $+ Sn$ Oxide $+$ thorium fluoride.
Si	SiO, ZnS, $CeO_2 + MgF_2$; $MgF_2 + ZnS$.
InSb	ZnS, $PbCl_2$, As_2S_3.
Cellophane	MgO.
Irtran 2	BaF_2 (anti-ref.); CeF_3, MgF_2, SiO_2, Al_2O_3, didymium fluoride.
Irtran 4	BaF_2.

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