Glass for Diamond Processing: A tale of two Outstanding Materials

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Abstract

This article aims to give a brief introduction on diamond, its important properties and processing techniques starting from a rough diamond, primarily for the readers from the non-diamond professionals. A sincere effort has been made to describe how chalcogenide glasses can play an important role for diamond processing, especially at the rough diamond inspection stage to help the diamond professionals for making a perfect process planning to realize an augmented profitability. Chalcogenide glass being a non-oxide and non-conventional glass, a brief overview on this glass, its important properties and specialized fabrication technique has been presented. Finally, diamond processing technique using chalcogenide glass and its advantages has been elucidated.

INTRODUCTION

Do you know that 92% of the world's diamonds are cut in Surat, India and earn India about 10 billion US$ in annual exports?[1]

Diamond is the hardest known natural material on the earth and the costliest gemstone. Raw diamonds are highly stressed in the presence of impurities and crystal imperfections. Its attributes pose diamond manufacturers with a great challenge since, its mechanical properties make it difficult to cut and polish. Any loss during processing will affect seriously the profitability[2].

To the common person, a rough, raw diamond piece appears very much like a dull piece of glass. Only when polished and facetted, does it ascend to its full glory, displaying the sparkling brightness and splash of colours for which it is famous. About half of its weight is lost when transforming a rough stone into a gem set in an item of jewellery[3] (Figure 1). Being the costliest gemstone, it is a huge loss for diamond processors. Extreme precautions are employed and the process is undertaken by professionals with expert knowledge, equipment and tools for the job since every single decision will impact on profitability[4]. Before the cutting and polishing process begins, a thorough examination of the rough diamond is conducted. In this article it will be covered how glass can play an important role for inspection of rough diamond pieces, in order to minimize losses during processing to yield maximum profit to the diamond processing industries. We can distinguish four different phases in diamond processing: drawing/marking, cleaving/sawing, bruiting and polishing. Before we go deeper in to the diamond processing, let us understand about this material and why it is the costliest gemstone in the universe and how glass can play a very vital role in diamond processing.

SOME IMPORTANT FACTS ABOUT DIAMOND

How diamond is formed

Diamonds are extremely rare, with concentrations of at most parts per billion in source rock. It is often said that a diamond is a chunk of coal that did well under extreme pressure. In fact, coal has rarely played any role in the formation of diamonds. The most diamonds that have been dated are much older than earth's first land plants, the source material of coal. Geologists believe that most of the diamonds are formed in the earth's mantle and are transported to the earth's surface by deep-source volcanic eruptions. The diamonds are formed from pure carbon in the mantle under extreme heat and pressure. One of the most fascinating aspects of a diamond is the amount of time it takes to form, the entire process takes between 1 billion and 3.3 billion years. Most were formed at depths between 150 and 250 kilometers in the Earth's mantle, these regions have high enough pressure ~4.5 GPa and temperature ~950 ^{0}C to allow diamonds to form and they are not convecting, so diamonds can be stored for billions of years until a kimberlite eruption samples them. Smithsonian researchers also found large number of tiny diamonds when they were cutting a sample from the Allen Hills meteorite. These diamonds in meteorites are thought to have formed in space through high-speed collisions similar to how diamonds form on earth at a meteorite impact sites. Synthetic diamonds can be grown from high-purity carbon under high pressures and temperatures or from hydrocarbon gas by chemical vapor deposition (CVD) technique. However, this article deals with only naturally occurring diamonds.

Important properties of diamonds

Diamonds possess many outstanding physical characteristics and they are most suitable for many versatile applications, besides its universal appeal as a gemstone in jewelleries. It has the highest hardness, least compressibility and highest thermal conductivity of any natural material. It has low adhesion and friction, and its coefficient of thermal expansion is extremely low. Its optical transparency extends from the far infrared to the deep ultraviolet, making it the most suitable candidate material for thermal imaging applications. It also has high electrical resistance. It is chemically inert, not reacting with most corrosive substances, and has excellent biological compatibility[5]. All these superior properties of diamond are attributed to its unique crystal structure. Diamond is a solid form of the element carbon with its atoms arranged in diamond cubic crystal structure. In diamond bonds are sp3 orbital hybrids and the atoms form tetrahedra with four nearest neighbors, which are rigid and strong. Of all known substances, diamond has the greatest number of atoms per unit volume that possibly makes it both the hardest and the least compressible[6].

The high hardness of diamond contributes to its suitability as a gemstone. It can be scratched by other diamonds only; it maintains its polish extremely well. Diamonds are naturally hydrophobic, which means the diamonds' surface cannot be wet by water. Most importantly at room temperature, diamonds do not react with any chemical reagents including strong acids and bases making them everlasting. The high dispersion of white light into spectral colors and its high brilliance induced by higher refractive index are the primary gemological characteristics of gem diamonds.

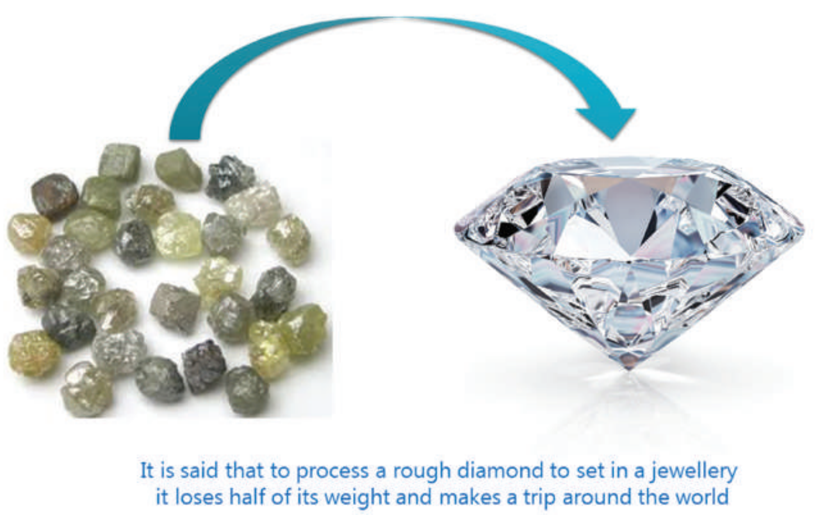

Fig. 1: How a rough diamond looks like and what we see in a jewellery set

DIAMOND PROCESSING

What is the 4 c's of diamonds?

A diamond's quality is determined by the 4C's:

- Cut: Quality of the angles, proportions, facets, and finishing details
- Color: How colorless the diamond is
- Clarity: How clean the diamond is of inclusions and blemishes
- Carat: The weight of the diamond

These four qualities of a diamond are the key components that impact its beauty and cost. The 4C's interact with each other within the diamond. They dictate how the diamond appears and how high quality it is. The prices of diamonds do not rise linearly with their quality and size. Instead, prices have an exponential relationship with the carat sizes. A large, flawless diamond is known as a paragon and the diamond processors devote their maximum time in the preliminary analysis of the rough stone for a perfect planning to extract flawless diamond pieces of maximum carat size out of a rough diamond. It needs to address a large number of issues, bears much responsibility, and therefore can last years in case of unique diamonds. The following issues are considered:

The hardness of diamond and its ability to cleave strongly depend on the crystal orientation.

- Most diamonds contain visible non-diamond inclusions and crystal flaws. The cutter has to decide which flaws are to be removed by the cutting and which could be kept.
- The diamond can be split by a single, well calculated blow of a hammer to a pointed tool, which is quick, but risky. Alternatively, it can be cut with a diamond saw, which is a more reliable but a tedious procedure.

After initial cutting, the diamond is shaped by means of numerous stages of polishing. Polishing removes material by gradual erosion and is extremely time-consuming. The associated steps are technically proven and can be performed with perfection by the technicians. The colours in the diamond evolve due to inclusion of other elements in the diamond crystal structure, although colourless diamonds are the costliest one. The perfect planning may hugely influence on the clarity and carat size of a diamond resulting in augmented profits.

HOW GLASS CAN PLAY AN IMPORTANT ROLE FOR MAKING A PERFECT PLAN FOR DIAMOND PROCESSING?

Diamonds are unstable against high temperature above 400 °C under atmospheric pressure[7]. The temperature of diamond ignition in pure oxygen is 690° C to 840° C. It is transparent from the far infrared to the deep ultraviolet region, i.e. it is transparent in visible spectrum as well and it has the highest refractive index of 2.417 at 589.29 nm wavelength.

The rough diamond inspections as well as planning for processing play a vital role for optimizing profitability. Historically the following methods are evolved for inspection of a rough diamond[8-9].

1. Without polished windows, without constructing a 3D model, without immersion:

   A diamond cutter looks through a magnifying glass at the diamond, trying to see and understand the inclusions and their many reflections. He identifies and locates the inclusions, weighs the stone, determines its shape, crystal structure, color and purity. Such a method is typically used during purchase of rough diamonds.

2. With polishing windows, without constructing a 3D model, without immersion:

   The expert first observes the stone, and then opens (polishes) a number (typically two), "windows" on opposite sides of the stone, such that he can look through one of these windows to see it, perceive inclusion against a background formed by the other window.

3. With polishing windows, with a 3D model of the diamond, without immersion:

   Typically, a number of windows are first polished for observing the inclusions. In the case of flat and solid facets of the rough stone, these facets can act as such useful windows. In a typical case, the windows must allow inclusions to be observed from at least two points of view. The stone is then glued to a holder, mounted in a scanner, and a 3D model of the diamond is constructed.

4. Without windows, with or without a 3D model of the diamond, using a liquid in which the diamond is immersed:

   In this technique a diamond is glued to the holder and immersed in an immersion liquid with the same refractive index as a diamond. Consequently, the diamond disappears into the liquid but the inclusions remain visible. The brick in the immersion fluid is rotated and 2D images are taken from multiple different viewing directions to determine a full 3D model of the inclusion or inclusions[10]. As an immersion fluid molten Se is used.

5. Without windows, with or without a 3D model of the diamond, using a solid medium in which the diamond is embedded:

   This can be considered as a latest technology employed so far for inspection of a rough diamond due to its several advantages like[11]:

   - There are no size limitations, as any size of diamond can be inspected

- The diamond need not be laser marked like older techniques. This gives one the freedom of re-trading if necessary
- Diamond's interior can be viewed with naked eyes or under loupe or microscope, making one feel more comfortable
- A rough estimation can be made, without even use of any machine or scanner
- Visibility of inclusions under normal lighting without any external aid that helps inspectors to check quality of a plot with highest accuracy
- An inclusion even in a highest clarity diamond (VVS1 grade) is easily visible
- It is a completely safe material at room temperature and can be handled by plotters without any health hazard
- Very cost-effective solution to chart inclusions in a rough diamond
- The immersion glass material can be reused

It is understood that if a rough diamond piece can be embedded within a transparent glass of matching refractive index with diamond, the whole interiors of the diamond become visible, even with a naked eye. It can now enable one to inspect the glass with absolute accuracy and to make a perfect planning to achieve maximum yields. Additionally, one can assess the stress distribution within a rough piece embedded in a glass using a polarimeter and can take measures to prevent unintentional breaking of a precious diamond by adopting stress removal measures. Now the glass has to have the following important properties to meet the above purpose:

6. It should have low melting temperature and enough fluidity below 300°C in order to embed the diamond.
7. The glass has to be highly transparent in visible spectrum.
8. The refractive index of glass needs to be matched with diamond i.e. 2.417 at 589.29 nm wavelength.

Now, no oxide glasses are known to have such a unique combination of optical and thermal properties (melting temperature <300°C). Only some novel chalcogenide glasses may exhibit such unique combination of properties and can impact diamond processing industries for an augmented profitability.

WHAT IS CHALCOGENIDE GLASS?

Chalcogenide glasses (ChGs) are non-oxide vitreous materials based on any of the chalcogen elements out of sulphur, selenium or tellurium from Group VIA of the periodic table or together with other network formers from Group VA (such as Sulphur, Sb) and Group IVA (such as Ge). These glasses do not contain any oxygen. Such glasses are covalently bonded, unlike oxide glasses. These glasses are famous for their unique properties and functionalities including large transmission window extended to far infrared (FIR) through visible, high refractive index, and most importantly low melting temperature. However, as it is a non-oxide glass, special synthesis technique is required to avoid oxygen contamination. In brief, glass composition is weighed and mixed in an atmosphere-controlled glove box filled with inert gases e.g., N2 or Ar. The glass batch is transferred to a silica ampule, which is further vacuum sealed to eliminate presence of any oxygen. The sealed ampule containing glass batch is then loaded within a rocking furnace that rocks continuously for about 12 hours for homogeneous mixing of the glass at the melting temperature. Once the melting is completed the ampule containing glass is quenched in air or water depending on the compositional requirement. The synthesis technique (schematic) of chalcogenide glass has been shown in Figure 2. The annealing of glass is carried out in an atmosphere-controlled oven, prior to collecting the glass by breaking the ampules. It is understood that specialized techniques/machineries

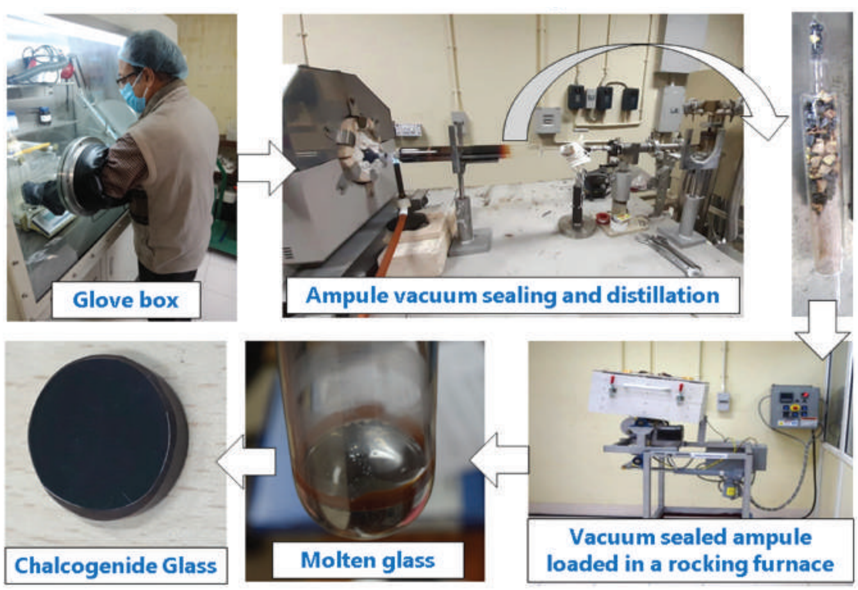

Fig. 2: A typical chalcogenide glass melting facility at CSIR-CGCRI, Kolkata

are employed for synthesis of non-oxide chalcogenide glasses. Due to furnace rocking mechanism and high vacuum ampule sealing arrangements, a limitation exists for production of chalcogenide glass in a large size and quantity. As such raw materials cost for such glasses are very high and due to this specialized technique of synthesis; chalcogenide glasses are relatively much costlier than conventional oxide glasses.

SOME IMPORTANT PROPERTIES OF CHALCOGENIDE GLASS

The elements forming chalcogenide glasses are generally covalently bonded due to the small difference in electronegativity between cations and anions. As a result, the strength of the bonding is lower than in oxide materials, making glass formation feasible over a large variety of compositions. The addition of Se increases the polarizability, because Se is larger than S, with weaker bonds that are more polarizable. Similarly, chalcogenide glasses containing Te are more polarizable than selenium and sulphur. Since, refractive index is directly related with the polarizability, higher refractive index is observed in case of presence of Te than Selenium and sulphur in a glass.

As mentioned previously, chalcogenide glasses present a wide transparency window in the infrared region. At the shorter wavelengths, the optical transmission window of a glass is limited by its band-gap, while at longer wavelengths it is limited by multi-phonon absorption. Therefore, the band gap shifts from visible with sulfur-based glasses to near infrared for selenium and tellurium-based glasses. Chalcogenide glasses present a transmission extending far in the infrared region, up to 11 μm for sulfide glasses, 16 μm for selenide glasses, and more than 20 μm for tellurium glasses, while the transmission of silica and fluoride glasses is limited to about 4 μm and 7 μm respectively. Hence, both the transmission window and refractive index of a chalcogenide glass can be tailored by selecting the composition of the glass.

Due to their high transparency in the infrared region, their ability to be shaped by molding and their lower cost as compared to other materials transmitting in the second and third atmospheric windows such as single crystalline germanium, chalcogenide glasses are used for a wide range of applications in the infrared optics. These applications comprise night vision, non-linear optics, chemical and biological sensing or optical fibers. Furthermore, variations in the glass stoichiometry can be easily carried out to adjust specific parameters such as the refractive indices.

The main strategy for synthesizing chalcogenide glasses is based on the creation of a covalent polymeric framework involving elements having similar electro-negativity. This means that the central elements such as S, Se or Te have to be combined with close neighbour atoms in the periodic table such as As, Sb, Ge, Ga, or I. Presence of As, Sb, Ge or I in the glass modifies its structure, thereby influencing glass property substantially[12]. Hence, by suitably selecting the glass compositions, its transparency, melting temperature and refractive index can be tailored to suit for diamond processing applications. Flaschen et al. was the first to give a general description of the properties of a series of low-melting glasses in the system arsenic-sulfur modified by bromine, iodine, and thallium[13]. The ternary iodine glasses possess remarkably low melting temperatures and are the first example of inorganic glasses having high fluidities at below 100°C. Compounds of this type were also reported by Goryunova and Kolomiets[14]. The As-S-I chalcohalide glass was also reported way back in 1963 by Lin and Ho[15] who demonstrated that As-S-I glasses exhibit excellent resistance to moisture and to acids, including HF. Such properties of chalcogenide glasses were also reported by the different groups[16]. Kurushkin and his group reported use of chalcogenide glass of the As_2S_3–I–Br system having refractive index (2.41) similar to natural diamonds as an ideal immersion medium for processing of diamonds[17].

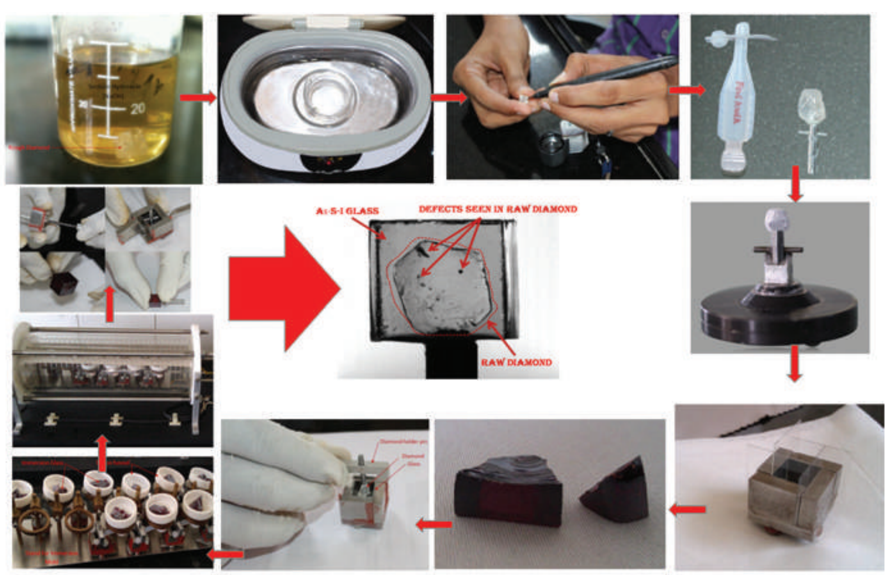

Fig. 3: Process flow chart for embedding rough diamonds in glass

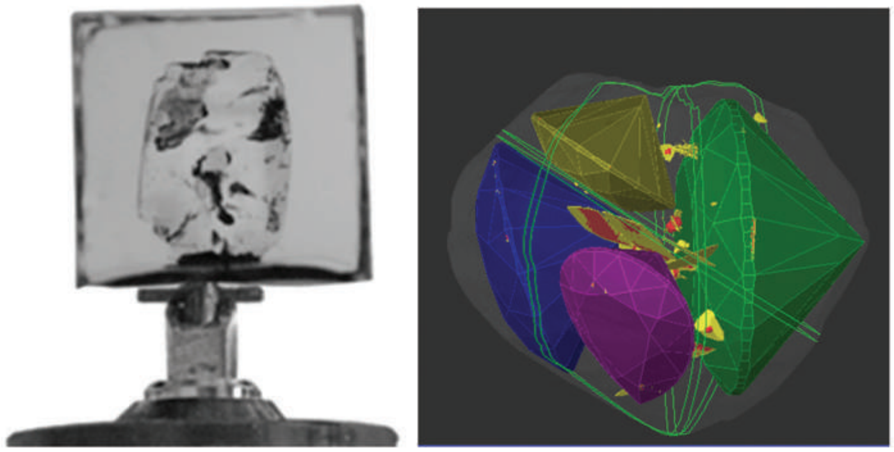

Fig. 4: A rough diamond is embedded in a chalcogenide glass making the internal defects visible, that helps in plotting[11] using software

CSIR-CGCRI researchers reported usage of As-S-I based low melting chalcogenide glasses for diamond processing in great details[18]. Waste's recycling of chalcogenide glass of the As–S–I system make the process even more economically viable[19] .

HOW DIAMONDS CAN BE PROCESSED USING SUCH CHALCOGENIDE GLASSES?

DIAMOND ENCAPSULATION:

An atmosphere-controlled furnace containing two chambers of differential pressure can be used for encapsulation of a rough diamond in a glass medium. One chamber containing the low melting chalcogenide glass in Teflon made crucible and the other chamber contains the raw diamond suitably hanged in a mica mold. The diamond encapsulation process has been shown in Figure 3. The crucible and the molds are connected by a pipe. Within the chamber, a differential pressure is maintained by using argon gas where crucible chamber is in higher pressure than the mold. Once the chamber containing the glass is heated up to say 200°C, the glass becomes fluid and due to differential pressure, the glass flows to the mold chamber and gradually covers the entire raw diamond piece. The furnace is then cooled to room temperature by natural cooling for taking out the glass encapsulated diamond (GED). There are other innovative methods available for diamond encapsulation in glass. The GED is shown in Figure 4 where defects within the diamond are clearly visible in naked eye. The GED is then placed under an optical microscope to see through the raw diamond to find defects, and suitable processing strategies are adopted with the help of softwares specially developed for this purpose to get maximum defect free diamond from the raw one.

CONCLUDING REMARKS:

Diamond processing using novel chalcogenide glasses is a unique approach towards establishing a cost-effective, user friendly potential technology. CSIR-Central Glass and Ceramic Research Institute, Kolkata has set up a state-of-the-art chalcogenide glass synthesis facility and formulated novel chalcogenide glasses for processing of rough diamonds and to observe stresses within it. The technology is proven and ready for commercialization.

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