CHAPTER 2

LITERATURE REVIEW

2.1 Background of Precious Stone

Gemstones have long been cherished for personal adornment. In addition, they are often used to represent wealth and strength. Some gemstones commemorate anniversary milestones. For instance, the ruby (red) is chosen to commemorate the 40th anniversary, whereas the sapphire (blue) commemorates the 45th anniversary, as shown in Figure 2.1. Similarly, the 60th anniversary is symbolized by the diamond. In addition, some gemstones are associated with an individual’s birth month, such as amethyst for February and aquamarine for March. For decades, gemstones such as emerald, sapphire, diamond, and ruby have been acknowledged as having outstanding value and appeal and are highly cherished for their color, clarity, brightness, and durability. Certain diamonds have a rich and interesting background that will add to their worth, such as the 170-ct red spinel called the Black Prince’s Ruby (Malsy & Klemm, 2010) that is set on the Imperial State Crown of England or the fancy 45.52-ct dark grayish-blue Hope Diamond of the Smithsonian Institution (Wise, 2021).

Source: Bowles (2021)

Figure 2.1 Ruby and Sapphire.

An allochromatic mineral, namely corundum (Al_2O_3) (Joseph et al., 2000), is a very durable material that has been a mainstay of the jewelry industry for centuries. Allochromatic minerals does not give off any color since it does not select any wavelength to be absorbed and transmit their color, hence, the pure corundum is in clear or colorless state (Juncomma et al., 2014).

Corundum is commonly present in igneous rocks that are undersaturated compared with silica in aluminous metamorphic rocks, such as the Nepheline syenites and aluminous xenoliths. It is the primary component of emery deposits and is known as a detrital mineral in sediments. Corundum exists in the form of nearly pure Al_2O_3 with small amounts of chromium (Cr), vanadium (V), iron (Fe), nickel (Ni), gallium (Ga), calcium (Ca), and manganese (Mn). Besides, sodium (Na), magnesium (Mg), silicon (Si), cobalt (Co), cadmium (Cd), sulfur (S) and zirconium (Zr) may also exist.

All these elements typically exist up to few hundred ppm; however, Cr can reach 2–3 wt%, and Fe can exceed 1 wt%. Furthermore, these impurities affect the corundum's color, resulting in red rubies, blue and green sapphires, and purple, orange, pink, and brown shades (Bowles, 2021).

Among all the gemstone corundum deposited in earth, ruby is the most prized color of corundum (Mcclure et al., 2006). Rubies are made from the mineral corundum or Al_2O_3. They are formed under the Earth's surface as Al_2O_3 is subjected to intense heat and pressure. Corundum, on the other hand, is created from closely packed oxygen and aluminum atoms, and this usually results in a material that is colorless. However, the stone can have different colors as other minerals or substances replace the Al atoms (Shah & Kankariya, n.d.). Rubies exhibit a noticeable color ranging from pink to blood red. The red color is primarily attained from the existence of a few percent of Cr atoms; "pigeon's blood" is considered the most brilliant, dazzling and most precious red color of rubies. There are only few part all over the world where rubies can be found because their existence solely depends on the geographical or geological origin (Keulen et al., 2020). The areas that contribute a lot to ruby production are Myanmar, Thailand, Vietnam, and Mozambique.

Besides the Cr-rich variety of corundum, other chromophores can be found in rubies, such as V and Fe atoms. Ruby is also a dichroic crystal, which reveals a distinct color (either purple or orange-red) depending on the direction of light within the gemstone (Giuliani et al., 2020). Table 2.1 shows the Mohs Hardness Scale for ten minerals found on Earth (King, n.d.). Scale 10 represents the hardest mineral, and scale 1 represents the least hard.

Table 2.1 Mohs Hardness Scale for Minerals.

Mohs Hardness Scale	
Minerals	**Hardness**
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Orthoclase	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

Source: King (n.d.)

Because of its vivid color and great light transmission, rubies have long been appreciated in the jewelry industry. Furthermore, they have been linked to positive health outcomes. The optical properties of rubies, as well as their extreme hardness (9 on the Mohs scale), high strength, thermal and chemical stability, exceptional thermal conductivity, high insulation, low coefficient of friction, and optical transparency, make them valuable materials for modern technological applications such as lasers, masers, optoelectronics, temperature sensors, and precision machinery devices (Liu et al., 2019).

2.2 Ruby Stone

Ruby is the red variety of gemstone corundum that is widely used in luminescence technologies (Novita et al., 2020), jewelry, and many other industrial materials owing to its outstanding mechanical, optical, and chemical properties (Ayuzawa et al., 2020). The global ruby trade has exploded in recent years, especially since rubies were discovered and mined in Mozambique in the previous decade (Merilee et al., 2015). The gemstone trade had experienced several changes and developments, together with difficulties. The complexity of ruby grading has been widely studied to assess the ruby grades. The study is very vast, up to the fact that researcher can conclude where does the studied ruby geographically came from (Palke et al., 2019b), optical phenomenon (refraction, reflection, dispersion and scattering of light) (Kiefert & Hänni, 2000) and so on. Improvements in grading are high in demand, particularly for the people buying and selling fine rubies. Figure 2.2 shows the top-grade rubies extracted from Montepuez, Mozambique.

Source: Merilee et al. (2015)

Figure 2.2 Top-Grade Rubies from Montepuez, Mozambique.

In this subsection, a detailed review of the grading criteria of ruby stones, the inclusions in rubies, and methods to improve the inclusions is given. Fundamentally, the focus is mainly on the clarity criteria of rubies.

2.2.1 Grading Criteria of Ruby Stones

Rubies are one of the most valuable gemstones on the world, and their demand for jewelry is usually high. Many jewelers are willing to risk a large sum of money in order to own this gemstone. As a result, many imitations of rubies have been created to meet this demand. However, complications occur when gemologists have to confirm the stone's grading value or quality. Natural rubies of excellent quality have become extremely uncommon due to rising demand and limited natural supply (Buaprasert et al., 2020). The ruby industry is tremendously profitable, but it is far more complicated than many ore industries, such as iron, silver, or gold, because ruby values are not based just on weight or purity. Furthermore, the significance of the ruby is dependent on a more complex quality because grading techniques include various aesthetic, subjective, and cultural elements.

Aside from the well-known and very detailed diamond trade system developed in the middle of the twentieth century based on the 4Cs (color, clarity, cut, and carat weight of the gemstone) (Moses et al., 2004), additional factors play a vital role for market demand value of colored stones such as rubies. (Giuliani et al., 2020). Figure 2.3 shows the difference in the appearance of a polished and rough ruby.

Source: *Ruby* (n.d.)

Figure 2.3 Polished (Left) and Rough Ruby (Right).

First, it must be known that the gemstone was directly mined and not produced from a factory. At the end of the 19th century, synthetic rubies were produced by either flux, flame fusion, or other hydrothermal processes.

If the presence of synthetic rubies caused any initial scandals and panic, the gemology trade associations responded by setting up gemological laboratories that have the capabilities to distinguish natural rubies from synthetic ones and thus re-establish the trust required to expand the trade. Second, for the final evaluation, improvements and treatments are also essential. Some very effective heat treatment techniques were developed in Thailand in the 1990s to meet the high demand for big, clean rubies.

These techniques were distinct from the conventional technique of blowpipe used for centuries in Sri Lanka as defined by many 10–11th century travelers starting with Al Burini (Giuliani et al., 2020). While blowpipes were used in some rubies to extract the purple part, the new technique went further as it could repair fractures in rubies using borax as a flux additive, thereby allowing large stones to be cut. Due to this and the following innovative treatment procedures, new deposits, such as Mong Hsu in eastern Myanmar, began to dominate the ruby trade in the early 1990s. Consequently, Thailand grew to its position as the world's largest ruby trading center (Giuliani et al., 2020).

2.2.1.1 Color

Gemstone colors are typically classified based on three variables: tone, hue, and saturation. Tone is the degree of absorption and reflection of light; it is the primary factor of color intensity. A hue is the color gradient of a pigment, such as dark or light. Finally, saturation is identified by observing how much of the main color is contained in the stone's color. Notably, the most sought after rubies are bright and predominantly red (Shah & Kankariya, n.d.).

The colors of rubies vary from extreme blackish red to orange or pinkish red. The main color is still red, regardless of the variations of other colors that may be a part of the ruby. Rubies that are too dark in hue can have the color of a wine vinous.This ruby's darkness has a rich color that can give less glow. True red rubies with a luxuriant, shiny, genuine red color are sometimes referred to as "pigeon blood" or Burmese red rubies (Mengich et al., 2019). Of all the rubies, these rubies are the most valued and precious (Shah & Kankariya, n.d.)

Another popular phrase used to identify marginally darker rubies is "royal red." Due to a higher iron content that exists naturally within these gemstones, they are a bit darker than the "pigeon blood" rubies. The high iron content reduces the amount of fluorescence and blue transmission, making the stone dark in color. Royal red rubies can be found in Mozambique, Thailand, Cambodia, Kenya, and Madagascar (Shah & Kankariya, n.d.).

Light rubies have an almost pink color. These light rubies are brighter than dark rubies and similar to a pink sapphire's hue. Rubies can be pleochroic, that is, they can reflect distinct color shades and have differing degrees of sparkle when rotated at various angles. Rubies often have fluorescence, which means that they can radiate light when placed under natural or artificial light. The consistency of the red color can be evaluated by human eyes. The ruby may not be of the optimal consistency if the eye sees traces of gray or brown (Shah & Kankariya, n.d.).

Hue is where the color appears around the scale of the color wheel. Red, green, and blue are the most fundamental and known colors seen by the eye. Other colors evolve when looking at colors between secondary colors, such as violet. Rubies similar to a genuine red on the color wheel scale are the most coveted in terms of their color. However, some may think it is attractive to have a flawless red, some may choose a color mixed or ruby shade tinted with secondary colors. People appear to be more drawn to heavily concentrated shades, that is, bright red rubies. It is also possible to describe saturation as the richness of the color. Rubies benefit from a natural fluorescence that helps them become much more saturated with a glowing red hue. A heavily saturated ruby has a red color that is pure and deep; however, an unsaturated ruby has undertones of gray, brown, and black. Gemstones with perfect saturation are scarce and, therefore, more costly (Shah & Kankariya, n.d.).

2.2.1.2 Cut

The cut of a ruby is one of the key variables deciding its worth, overall attractiveness, and appeal. The ruby crystal's composition is the key factor determining its cut. It is possible to cut rubies into many shapes and sizes. Different aspects are considered while forming ruby gemstones from a raw ruby deposit. Rubies are most often sliced into cushions and circular shapes. The ruby adopts the same traditional shapes as the diamond shapes. However, most of the carat weight is preserved at the bottom of rubies in most cases. Therefore, when viewed face-up, a round-shaped rubies with the same carat weight as the cushions and oval shape rubies would have a smaller millimeter. Circular, cushion, and oval shaped rubies are extensively used in pendants, rings, and earrings. Among them, the round shape is common, although more rough wastage is produced. These shapes are available in different sizes for these purposes. Cutters also prefer not to cut very small sizes of rubies because they can look very similar to a circular shape (Shah & Kankariya, n.d.).

Source: Hsu & Lucas (2016)

Figure 2.4 This Ruby was Recut into 17.14 ct from 21.17 ct to Improve the Appearance.

Some rubies are cut to improve the appearance of the stone. For example, the ruby in Figure 2.4 was cut from originally 45.37 to 21.17 ct and then recut again to 17.14 ct, where in each cut, some inclusions are removed, resulting in a better color and clarity of ruby (Hsu & Lucas, 2016).

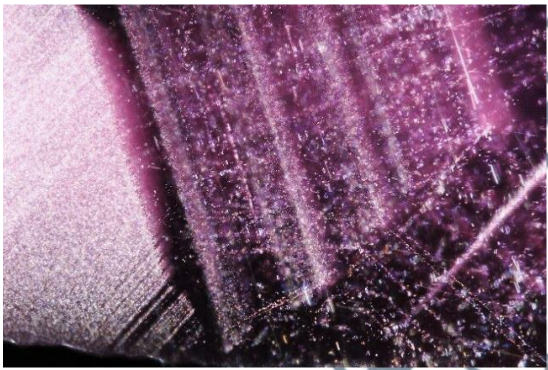
2.2.1.3 Clarity

For other natural gemstones, rubies have inclusions that develop within the gemstones during its formation. The amalgamation of different minerals and substances forms a ruby, so each piece is special. Clarity refers to the presence of inclusions and blemishes, which may affect clarity, emission of light and reflection from rubies. Inclusions refer to the irregularities that occur inside rubies (“Beginning Jewelry Sales 7,” 2014). Inclusions influence the ruby’s light output and color (Shah & Kankariya, n.d.). A vast majority of natural rubies contains inclusions, and rubies that have no inclusions are immensely rare and highly regarded.

On the other hand, blemishes represent irregularities on the surface of rubies, such as scratches (“Beginning Jewelry Sales 7,” 2014). The clarity grade of a ruby is determined by a professional grader using a microscope with minimum of ten times magnification. After evaluating all the criteria, the grader will assign the clarity grade that implies the visibility, together with any effect on the appearance or durability (“Beginning Jewelry Sales 7,” 2014).

2.2.2 Types of Inclusions in Ruby

Within a ruby, various types of inclusions are formed. Each has a distinct framework and, equally, a different appearance. Various inclusion types can influence the quality of rubies in several ways. Inclusions such as in Figure 2.5 can usually be observed through the naked eye, whereas some can be seen with a ten times microscope as shown in Figure 2.6 (Shah & Kankariya, n.d.).



Source: Vertriest & Saeseaw (2019)

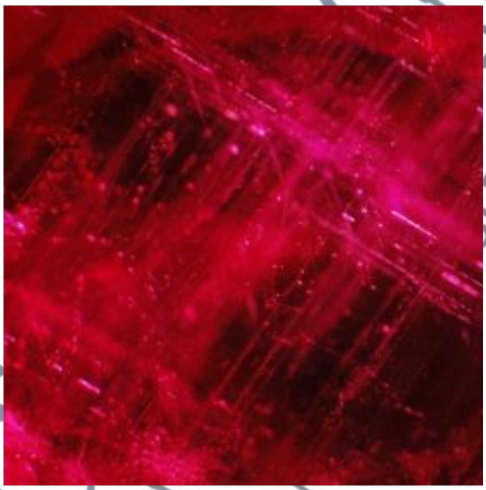
Figure 2.5 Common Inclusions Found in the Mozambique Rubies.

Source: "Beginning Jewelry Sales 7" (2014)

Figure 2.6 Grade Clarity of Gemstones is Graded by Most Professional Lab Graders using a Microscope.

2.2.2.1 Silk

Such inclusions mimic silk fibers as shown in Figure 2.7, typically found in clusters. They are present on a ruby's inside and look like fine fibers. These inclusions can slightly influence the color and transparency of rubies. They may whiten the ruby extensively and discolor the exquisite red shimmer and hue. They may also influence the light output (Shah & Kankariya, n.d.). Smaller particles and platelets can be difficult to see without fiber-optic illumination at a proper angle (Vertriest & Saeseaw, 2019).

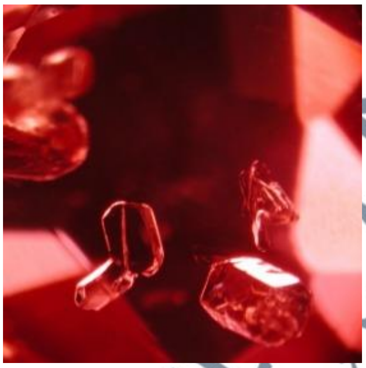


Source: Shah & Kankariya (n.d.)

Figure 2.7 Ruby Inclusions: Silk.

2.2.2.2 Crystals

These inclusions are particularly solid, with varying shapes and sizes. They may look like small pinpoints or grains. Because crystals are usually white or black, the effect of inclusions on the color, brightness, and light output of rubies is important. Although inclusions are present in all rubies, crystal inclusions such as in Figure 2.8 should be avoided as they affect the rubies appearances more (Shah & Kankariya, n.d.).

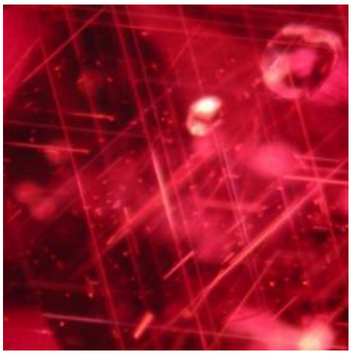


Source: Shah & Kankariya (n.d.)

Figure 2.8 Ruby Inclusions: Crystal.

2.2.2.3 Needles

Some inclusions are long and thin, like crystals or narrow tubes, as shown in Figure 2.9. They always look a little glassy and have an influence on the light output but less on color. On magnification, a pattern of scratches appears inside the ruby (Shah & Kankariya, n.d.). These oriented needles and particles are frequently formed in bands following the corundum growth structure (Vertriest & Saeseaw, 2019).



Source: Shah & Kankariya (n.d.)

Figure 2.9 Ruby Inclusions: Needles.

2.2.2.4 Cracks and Feathers

Fractures and fissures that may be featherlike in nature as shown in Figure 2.10 are also found in rubies. The inclusions can break the surface and damage the structural stability of rubies. Because rubies are soft, these inclusions can be risky when their scale is significant (Shah & Kankariya, n.d.).

Source: Shah & Kankariya (n.d.)

Figure 2.10 Ruby Inclusions: Feathers.

2.2.2.5 Twinning

Twinning also indicates crystal inclusions, but two structural inclusions grow out of each other. Twinning makes crystals inclusions more transparent as the overall crystal's size increases. Depending on the color of the crystal, twinning may affect the brightness of the inclusion and decrease the light output, making the crystal lighter or darker in color (Shah & Kankariya, n.d.).

2.2.2.6 Fingerprints

Fingerprints are widespread in rubies. The inclusions are gathered, which may seem like tiny fingerprints of humans. They are less likely to influence the ruby's consistency because they are minimal. However, if a ruby contains large amounts of it, the light performance and red hue gets affected (Shah & Kankariya, n.d.).

2.2.2.7 Cavity

Cavities are minuscule holes that extend from the surface into the inside of a ruby. Visually, large cavities are unappealing and make a ruby seem shattered. In certain cases, while placing the ruby in jewelry, its structural integrity can get affected due to cavities (Shah & Kankariya, n.d.)

2.2.2.8 Scratches and Abrasions

Scratches and abrasions are blemishes on the ruby's surface that appear like rough scrapings. Scratches can be polished away; still, it depends on the scratch's height, position, and width. If it is profound, a scratch can result in a lot of weight loss. Additionally, because they are surface inclusions, scratches are generally very visible (Shah & Kankariya, n.d.).

2.2.2.9 Color Zoning

Although all rubies are predominantly red, they have other secondary colors. Uneven shades develop when the hue on the ruby's surface does not appear uniform. Color zoning will also trigger inclusions that cause the areas of the ruby to appear pink. Color zoning is also influenced by the ruby's cutting. Cutters strive to retain the red hue and tone for maintaining the uniformity of the color (Shah & Kankariya, n.d.).

Inclusions can undergo some treatment to improve the appearance of rubies. For instance, the ruby in Figure 2.11 (left) shows highly visible fissures that can reduce its attractiveness. The ruby on the right had undergone some treatment that reduced the visibility of the fissures and increased its clarity simultaneously. A high-grade ruby has the slightest presence of inclusions and a clean appearance as the Mozambique ruby shown in Figure 2.12.

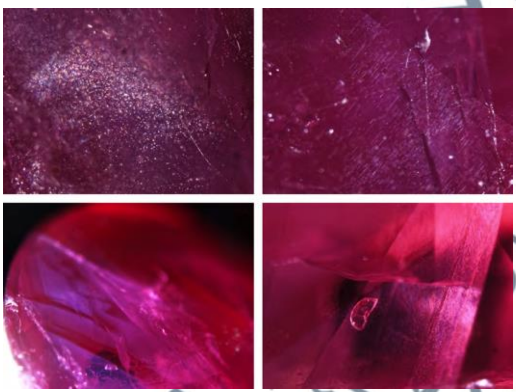
Source: Hsu & Lucas (2016)

Figure 2.11 Before Treatment, Nonuniform Clarity and Highly Visible Fissures Appear in the Left Ruby. The Less Visible Fissure and More Uniform Clarity Appear on the Right Ruby after Treatment.

Source: Vertriest & Saeseaw (2019)

Figure 2.12 A Clean Mozambique Ruby Viewed under Brightfield Illumination.

Inclusions are useful for determining the origin of rubies (Sorokina et al., 2015). In July 2016, eight faceted rubies from Pokot in the Western Province of Kenya were submitted to the Gemological Institute of America in Bangkok laboratory. These rubies had inclusions similar to those seen in rubies from Myanmar or Luc Yen, Vietnam, as shown in Figure 2.13 (Sorokina et al., 2015). This discovery gives a new challenge (Ahline, 2020) in determining the origin of rubies, as the information in the previous database indicates that such inclusions only appear in rubies from Myanmar or Vietnam (Saeseaw et al., 2016). This shows that gemologists, as well as geologists, particularly in the jewelry industry, need a new standardized and quantitative technique to analyse rubies. Some of the latest types of inclusions discovered in rubies are the amphibole mineral inclusions (Moses & McClure, 2010), chrysoberyl inclusions, snowflake inclusions, and lazurite inclusions (Gabriel Angarita et al., 2020).



Source: Saeseaw et al. (2016)

Figure 2.13 Inclusions Found in the Rubies from Pokot that are Similar to the Rubies in Myanmar and Vietnam.

2.2.3 Types of Rubies

Source: Shah & Kankariya (n.d.)

Figure 2.14 Different Ruby Grades.

Figure 2.14 illustrates different ruby grades. The grades AAA and AA rubies are considered high grades, with each covering 1% and 10% of natural gemstones, respectively. These rubies are classified as rare and expensive gemstones, and they are the best grade used for fine jewelry (Shah & Kankariya, n.d.). In comparison, the grade A rubies are considered medium-grade rubies.

This type of ruby constitutes for 50 %–75 % of all natural rubies and is commonly used in fine jewelry (Godha, 2014). Furthermore, the lowest grade of ruby is grade B, which are found among all available natural rubies (Shah & Kankariya, n.d.).

2.2.4 Physical and Optical Characteristics of Ruby Stones

Ruby is in the corundum mineral class of high hardness (9 on the Mohs scale). It has low reflectance and high hardness. The significant hardness can cause problems during polishing, producing many surface scratches. Therefore, scratches can act as a recognition guide as they represent some elements that appear in rubies (Bowles, 2021).

The structural form of rubies (α-Al_2O_3) is generated by replacing a small amount of Al^{3+} ions with Cr_3^+ ions. These Cr^{3+} ions, along with traces of other impurities (such as Fe^{3+}, Ti^{4+}, V^{3+}, Mg^{3+}, Si^{4+}), give the red color of the natural ruby (Palakawong et al., 2021).

Ruby has a degree of transparency from completely transparent to opaque and a refractive index from 1.762 to 1.770 according to the Gemological Institute of America

(GIA) database. The gemstone's base appearance or luster is vitreous. Once polished, the surfaces of the gemstone vary from vitreous (glass-like appearances) to sub adamantine (almost incapable of being broken, dissolved, or penetrated) (*Physical & Optical Properties of Corundum, Rubies, Sapphires*, n.d.). The specific gravity or density of ruby is in the range of 3.9 to 4.1 (Friedman, 2021). Ruby has a light reflectance value of 14 (Gooch, 2011).

In fact, all pink, purple, red, and orangey-pink gemstones gain their color due to the existence of a 550-nm absorption band. Slight changes in the band characteristics combined with other deficiencies (such as trinitrogen ion (N^{3-}) and triatomic hydrogen ion (H^{3+}) where both are unstable molecules) contribute to differences in hue and saturation (Eaton-Magaña et al., 2017). In terms of fluorescence, rubies show intense red fluorescence in long-wave ultraviolet (UV) light except when quenched with iron (Fetherston et al., 2013).

2.3 Gemology Tools

Gemology involves investigation of the optical and physical properties of gemstones that make them special. Gemstone detection requires the study of these properties to differentiate between different types of gems. Many gemological instruments are used to differentiate or quantify these criteria (Clark, n.d.). Haüy and his peers started the development of gemology as modern science in 1817 (Fritsch & Rondeau, 2009). The invention of gemological tools such as polarizing filters (made of gemstone tourmaline) and refractometers occurred in the 19^{th} century. Both types of equipment are still essential to gemological identification (Fritsch & Rondeau, 2009).

Nowadays, high-quality gemstones are often imitated in the trading market due to the existence of synthetic and treated gemstones, causing frauds and a great loss to consumers. Furthermore, identification instruments are typically large, heavy, and costly. To avoid false results when using detection tools, experience and operating skills are required (Liao et al., 2016). Usually, gemologists analyze the gemstones using tools that visually magnify them as shown in Figure 2.15.

Source: Hughes et al. (n.d.)

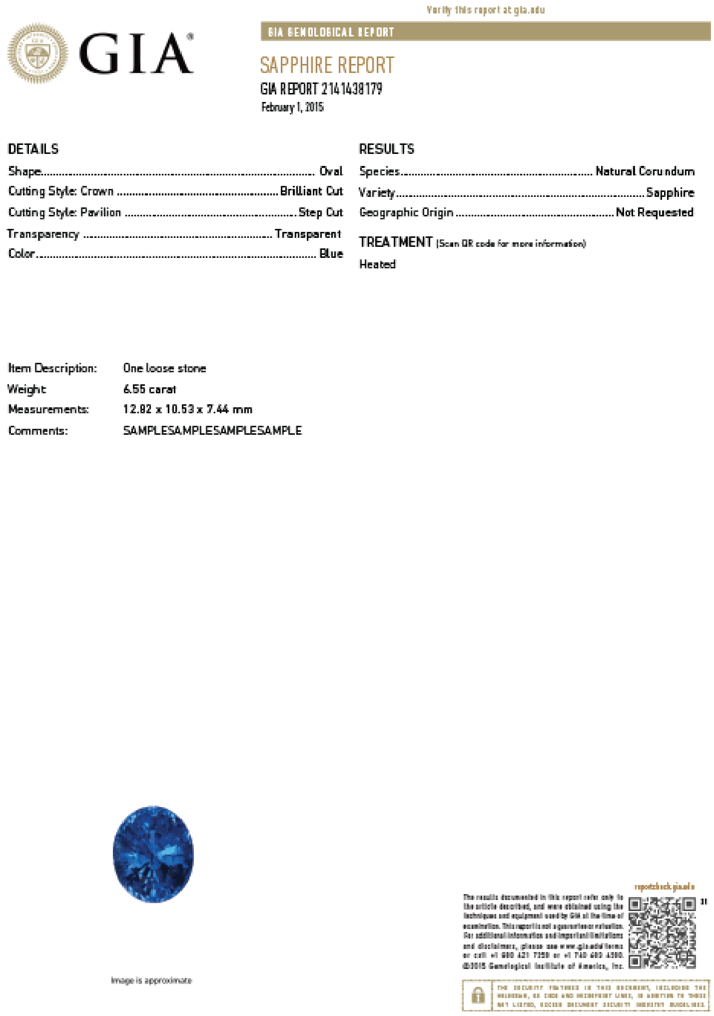
Figure 2.15 Gemologist Judging the Quality of a Gemstone.

The International Gemstone Society stated that the must-have tools in the gemology laboratory are a loupe and microscope to magnify the gemstone, refractometer to measure the refractive index, birefringence, and optical properties of gemstones, dichroscope, polariscope, and spectroscope. These tools are usually used together with other miscellaneous tools, such as the jeweler's eyes, diamond detectors, and hardness sets (Clark, n.d.). However, these tools are prone to errors as they depend primarily on human vision. Figure 2.16 shows some of the rubies displayed at the Geology Museum in Perak.

Figure 2.16 Some of the Rubies Displayed in the Geology Museum, Perak.

The GIA conducts research and provides education on gemstones and jewelry. This institute established the 4Cs and the International Diamond Grading System in the 1940s as the worldwide standard for diamond quality evaluation, which prevails until today (*The GIA Difference*, n.d.). The GIA also provides services to evaluate the gemstones. The GIA Identification Report (Figure 2.17) suggests if a stone is natural or man-made, as well as specifies its type and any visible treatments. This report also includes a photograph of the gemstone as well as a complete description of its cut, shape, weight, measurement, and color (*Sample Colored Stone Reports*, n.d.).

Moreover, the GIA Identification & Origin Report (Figure 2.18) indicates whether a stone is natural or synthetic, specifies the type of gemstones well as suggests the stone's geographic origin and any observable treatments. This report also includes a photograph of the gemstones as well as a full description of its cut, shape, weight, measurement, and color. Unfortunately, this report is limited to ruby, sapphire, emerald, Paraiba tourmaline, red spinel, and alexandrite only (*Sample Colored Stone Reports*, n.d.).


Verify this report at gia.edu

GIA GEMOLOGICAL REPORT

SAPPHIRE REPORT

GIA REPORT 2141438179

February 1, 2015

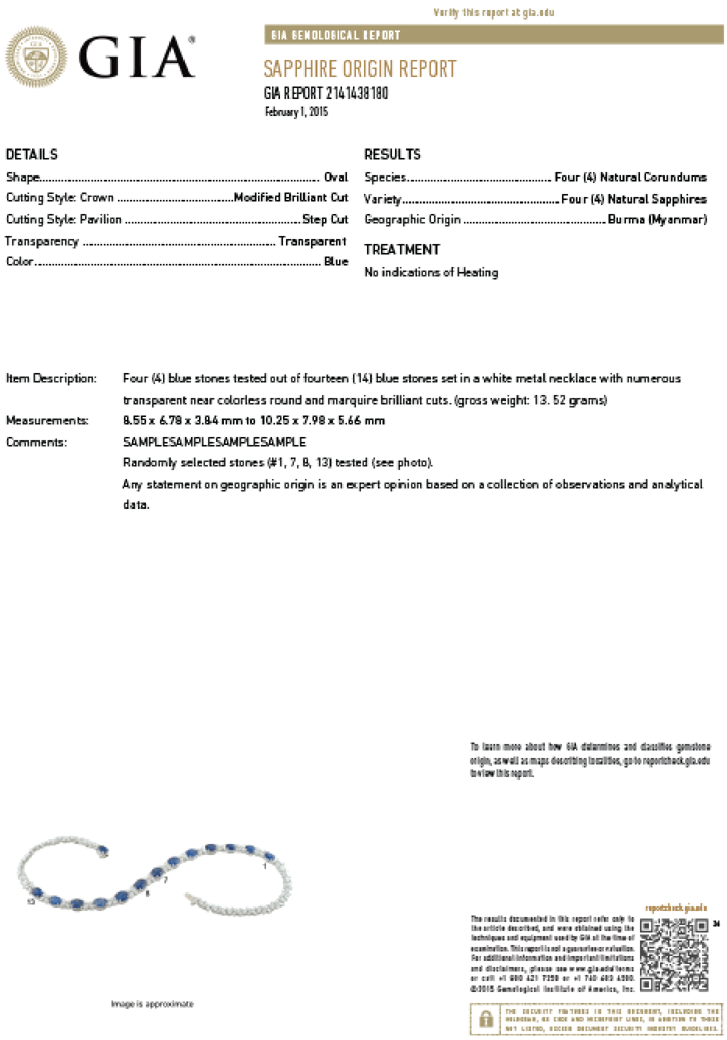
DETAILS		RESULTS	
Shape	Oval	Species	Natural Corundum
Cutting Style: Crown	Brilliant Cut	Variety	Sapphire
Cutting Style: Pavilion	Step Cut	Geographic Origin	Not Requested
Transparency	Transparent	TREATMENT (Scan QR code for more information)	Heated
Color	Blue		

Item Description:	One loose stone
Weight	6.55 carat
Measurements:	12.82 x 10.53 x 7.44 mm
Comments:	SAMPLESAMPLESAMPLESAMPLE

Image is approximate

Source: *Sample Colored Stone Reports* (n.d.)

Figure 2.17 Gemological Institute of America Identification Report.



Verify this report at gia.edu

GIA

GIA GEMOLOGICAL REPORT

SAPPHIRE ORIGIN REPORT

GIA REPORT 2141438180

February 1, 2015

DETAILS

Shape	Oval
Cutting Style: Crown	Modified Brilliant Cut
Cutting Style: Pavilion	Step Cut
Transparency	Transparent
Color	Blue

RESULTS

Species	Four (4) Natural Corundums
Variety	Four (4) Natural Sapphires
Geographic Origin	Burma (Myanmar)

TREATMENT

No indications of Heating

Item Description: Four (4) blue stones tested out of fourteen (14) blue stones set in a white metal necklace with numerous transparent near colorless round and marquire brilliant cuts. (gross weight: 13. 52 grams)

Measurements: 8.55 x 6.78 x 3.84 mm to 10.25 x 7.98 x 5.66 mm

Comments: SAMPLESAMPLESAMPLESAMPLE

Randomly selected stones (#1, 7, 8, 13) tested (see photo).

Any statement on geographic origin is an expert opinion based on a collection of observations and analytical data.

To learn more about how GIA determines and classifies gemstone origin, as well as maps describing localities, go to reportcheck.gia.edu to view this report.

Image is approximate

reportcheck.gia.edu

The results documented in this report refer only to the article described, and were obtained using the techniques and equipment used by GIA at the time of examination. This report is not a guarantee or valuation. For additional information and important limitations and disclaimers, please see www.gia.edu/terms or call +1 800 421 7250 or +1 760 603 4500. ©2015 Gemological Institute of America, Inc.

Source: *Sample Colored Stone Reports* (n.d.)

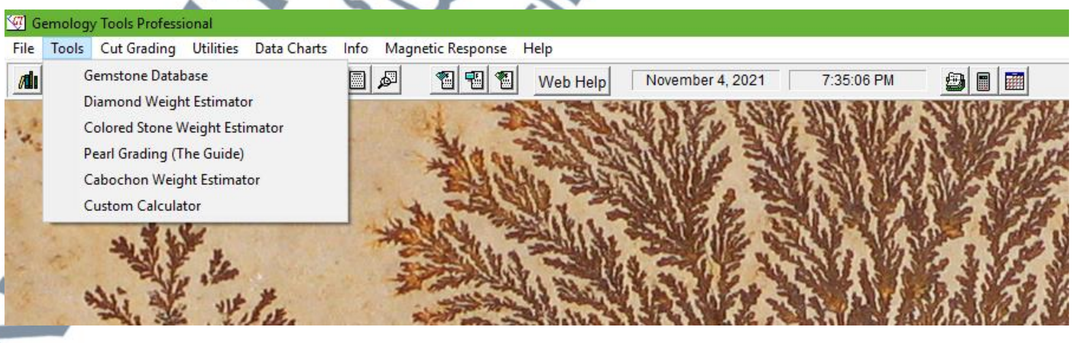
Figure 2.18 Gemological Institute of America Identification and Origin Report.

The Gemology Tools Professional software (Figure 2.19) comprises the most comprehensive gemology references. This software holds large information on various types of gemstones in the form of a database. Data constituting weight, inclusions, carat, and almost all details on gemstones are stored in this software. This software helps researchers and appraisers determine the gemstones' grades by comparing the data (*Gemology Tools Professional*, 2016).

Source: *Gemology Tools Professional* (2016)

Figure 2.19 Gemology Tools Professional Software.

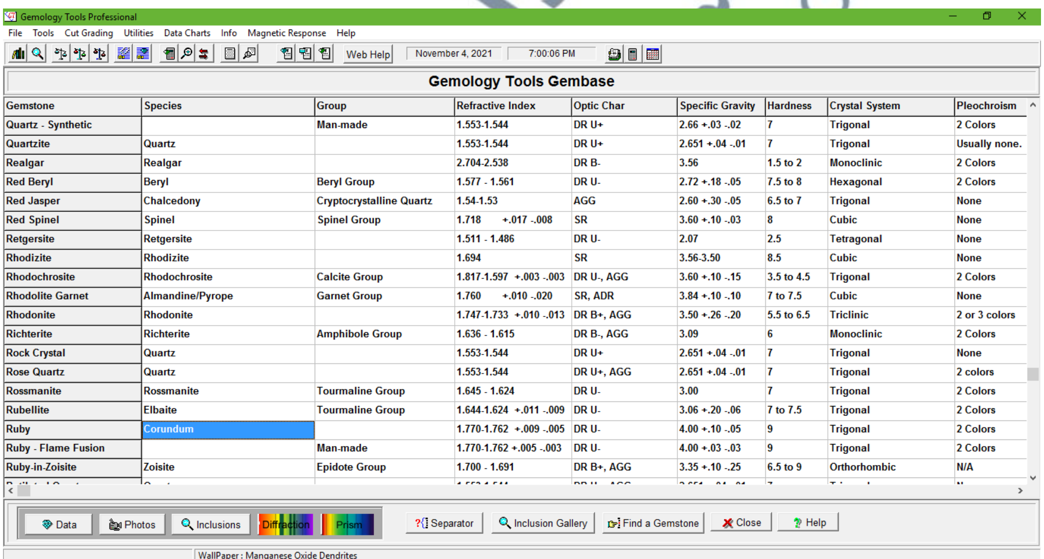
The Gemology Tools Professional software provides useful tools such as the gemstone database, diamond weight estimator, colored stone weight estimator, a guide to pearl grading, and cabochon weight estimator as depicted in Figure 2.20. This tool helps gemologists estimate the weight, chemical compound, and grades of gemstones based on the database (*Gemology Tools Professional*, 2016).



Source: *Gemology Tools Professional* (2016)

Figure 2.20 Features Options in the “Tools” Tab in the Gemology Tools Professional Software.

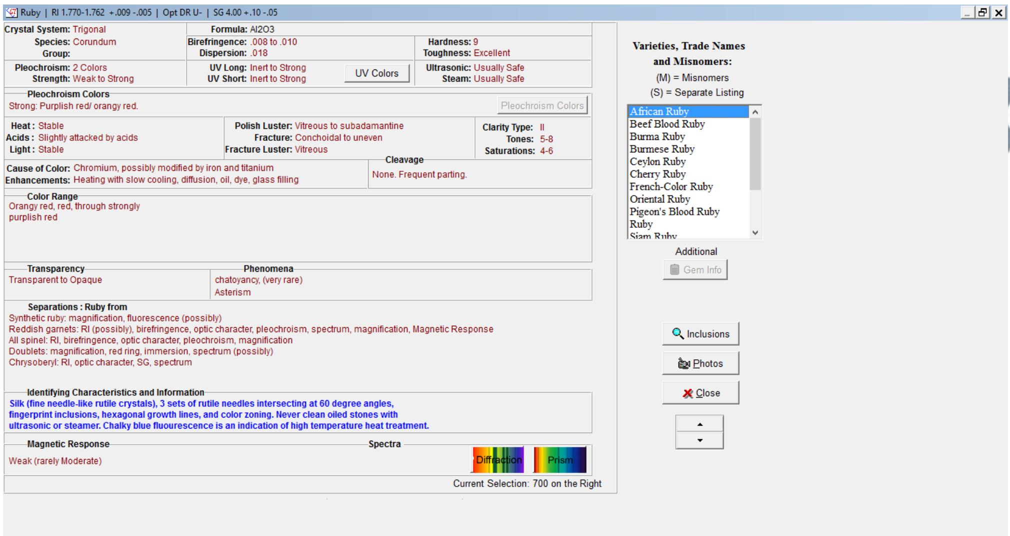
The gemstone database contains data of approximately 590 types of gemstones. The data covers all details on the species, group, refractive index, optical characteristics, specific gravity, hardness, crystal system, strength, clarity type, birefringence, and dispersion of gemstones as shown in Figure 2.21. The detailed information on ruby stones in Gemology Tools Professional software is shown in Figure 2.22. Furthermore, the data of inclusions in rubies is also available in this software as shown in Figure 2.23. The most important information on rubies used in this research is the refractive index, which vary from 1.762 to 1.770, as stated in the Gemology Tools Professional software (*Gemology Tools Professional*, 2016).



Gemstone	Species	Group	Refractive Index	Optic Char	Specific Gravity	Hardness	Crystal System	Pleochroism
Quartz - Synthetic		Man-made	1.553-1.544	DR U+	2.66 +.03 -.02	7	Trigonal	2 Colors
Quartzite	Quartz		1.553-1.544	DR U+	2.651 +.04 -.01	7	Trigonal	Usually none.
Realgar	Realgar		2.704-2.538	DR B-	3.56	1.5 to 2	Monoclinic	2 Colors
Red Beryl	Beryl	Beryl Group	1.577 - 1.561	DR U-	2.72 +.18 -.05	7.5 to 8	Hexagonal	2 Colors
Red Jasper	Chalcedony	Cryptocrystalline Quartz	1.54-1.53	AGG	2.60 +.30 -.05	6.5 to 7	Trigonal	None
Red Spinel	Spinel	Spinel Group	1.718 +.017 -.008	SR	3.60 +.10 -.03	8	Cubic	None
Retgersite	Retgersite		1.511 - 1.486	DR U-	2.07	2.5	Tetragonal	None
Rhodizite	Rhodizite		1.694	SR	3.56-3.50	8.5	Cubic	None
Rhodochrosite	Rhodochrosite	Calcite Group	1.817-1.597 +.003 -.003	DR U-, AGG	3.60 +.10 -.15	3.5 to 4.5	Trigonal	2 Colors
Rhodolite Garnet	Almandine/Pyrope	Garnet Group	1.760 +.010 -.020	SR, ADR	3.84 +.10 -.10	7 to 7.5	Cubic	None
Rhodonite	Rhodonite		1.747-1.733 +.010 -.013	DR B+, AGG	3.50 +.26 -.20	5.5 to 6.5	Triclinic	2 or 3 colors
Richterite	Richterite	Amphibole Group	1.636 - 1.615	DR B-, AGG	3.09	6	Monoclinic	2 Colors
Rock Crystal	Quartz		1.553-1.544	DR U+	2.651 +.04 -.01	7	Trigonal	None
Rose Quartz	Quartz		1.553-1.544	DR U+, AGG	2.651 +.04 -.01	7	Trigonal	2 colors
Rossmanite	Rossmanite	Tourmaline Group	1.645 - 1.624	DR U-	3.00	7	Trigonal	2 Colors
Rubellite	Elbaite	Tourmaline Group	1.644-1.624 +.011 -.009	DR U-	3.06 +.20 -.06	7 to 7.5	Trigonal	2 Colors
Ruby	Corundum		1.770-1.762 +.009 -.005	DR U-	4.00 +.10 -.05	9	Trigonal	2 Colors
Ruby - Flame Fusion		Man-made	1.770-1.762 +.005 -.003	DR U-	4.00 +.03 -.03	9	Trigonal	2 Colors
Ruby-in-Zoisite	Zoisite	Epidote Group	1.700 - 1.691	DR B+, AGG	3.35 +.10 -.25	6.5 to 9	Orthorhombic	N/A

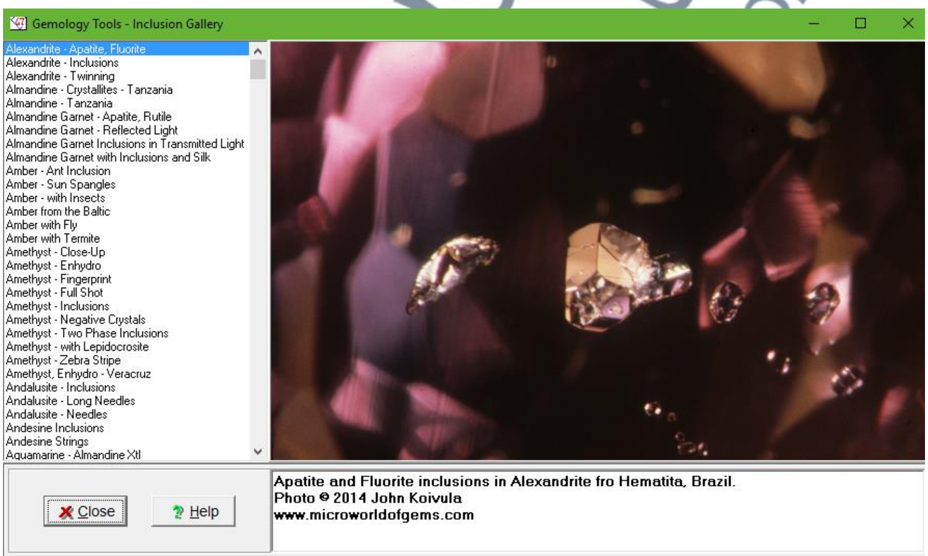
Source: *Gemology Tools Professional* (2016)

Figure 2.21 Gemology Tools Gemstone Base in the Gemology Tools Professional Software.



Source: *Gemology Tools Professional* (2016)

Figure 2.22 Detail Database of Rubies in the Gemology Tools Professional Software.



Source: *Gemology Tools Professional* (2016)

Figure 2.23 Inclusion Gallery in the Gemology Tools Professional Software.

The latest popular methods for analyzing gemstones involve determination of their origin. The methods involved in the analytical origin determination include the identification of physical properties, inclusions, spectroscopic characteristics, trace element chemistry, and isotopic chemistry. Inclusions can also be identified using microscopy and spectroscopy techniques.

The traditional technique involves visual identification of the inclusions and comparison with the references to known inclusions. Improvements of the visual identification of the inclusions have been made by observing and analyzing the inclusions using microscopy and spectroscopy techniques (Groat et al., 2019).

Optical microscopy technique is used to analyze the optical characteristics of the gemstones, such as refractive indices and birefringence. In addition, the growth features, solid inclusions (particularly morphology and color), and fluid inclusions that show the shape and ratios of the solid–liquid–vapor can identify the gemstone's origin. The finest quality has few inclusions of any type. A binocular microscope such as in Figure 2.24 is a commonly used tool in gemology laboratories together with darkfield illumination.

Darkfield illumination causes lights to invade gemstones from a wide range of angles rather than from below only. This helps the gemologists visually by providing a high contrast of a stone's inclusions. This technique is often applied for highlighting the rutile silk inclusions in sapphires and rubies using an intense fiber-optic light (Groat et al., 2019). Other tools involved in the analysis of gemstones are polarized microscopes and gravity meters as depicted in Figure 2.25 and Figure 2.26 respectively.

Figure 2.24 Binocular Microscope Displayed in Geology Museum, Perak, which is Used for Observing Gemstones.

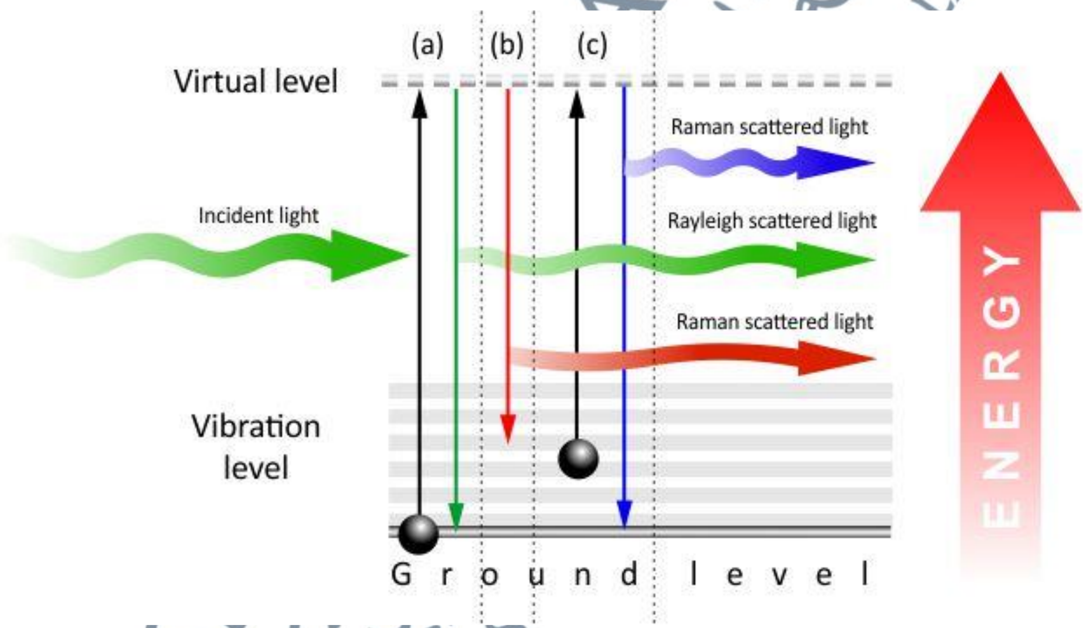
Figure 2.25 Polarized Microscope Displayed in Geology Museum, Perak.

Figure 2.26 Gravity Meter Displayed in Geology Museum, Perak.

Studies on color, luster, and morphology help identify solid and liquid inclusions in gemstones. These features are then compared to the geological origins data to determine their origin. After conducting the microscopic analysis, Raman spectroscopy is used to confirm the analysis of the inclusions. Microscopic techniques are always the first step in determining the heat-treated and synthetic gemstones (Palke et al., 2019a). When a laser is beamed through ruby or other gemstones, the reflected lights show two phenomena which are the Rayleigh scattering and Raman scattering.

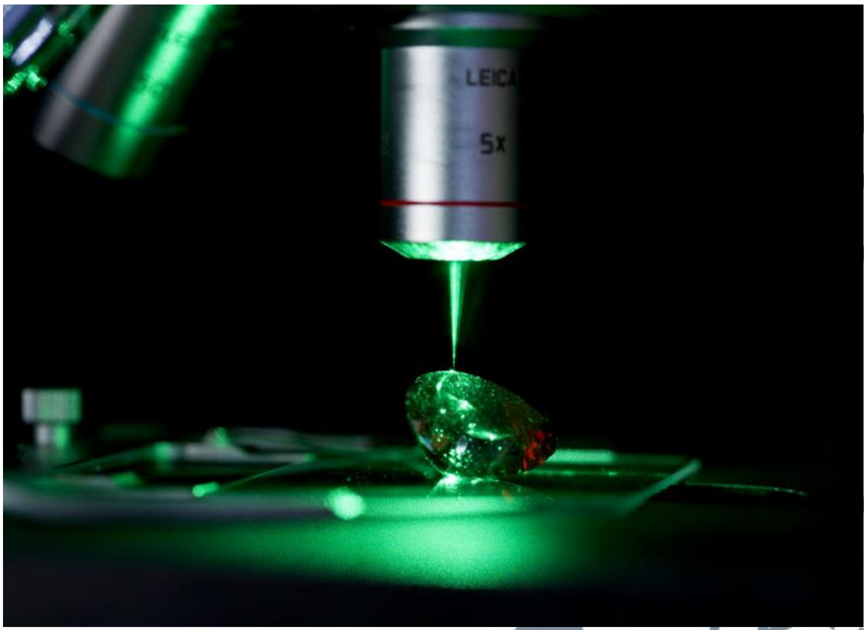
The first is called Rayleigh scattering. When a laser (incident light) is transmitted into the ruby, the photon from the laser beam interacts with the molecule in the ruby and excites the electron in them. The excited electrons are in a 'virtual level', which is not stable, so the electrons immediately fall down to the ground level and no energy changes occur, thus re-emitting light of the same wavelength (*Raman Spectroscopy*, n.d.). Raman scattering on the other hand, after electron is being excited, the electron falls to a level called as vibrational level, instead of the ground level. This causes that molecule to absorb or release an amount of energy, thus emitting longer or shorter wavelength of light, respectively. These are also called as 'Raman Stokes' and 'Raman Anti-Stokes', respectively (*Raman Spectroscopy*, n.d.). Figure 2.27 illustrates the energy level diagram for Raman spectroscopy process. It is caused by the presence of different molecular vibrations in the solid and fluid compositions of the stone. This information is then compared to the reliable reference spectra, such as the RRUFF database (Groat et al., 2019).

From the comparison of the spectra with the RRUFF database, the researchers can identify which chemical composition appears in the ruby and thus, they can conclude where the origin of the ruby base on its geographical structure. However, Raman spectroscopy is applicable for stones with a certain amount of fluorescence because a high amount of fluorescence obscures the Raman spectrum data, resulting in errors (Wang et al., 2019). Figure 2.28 demonstrates the confocal Raman spectroscopy technique used in gemology laboratories.



Source: Raman Spectroscopy (n.d.)

Figure 2.27 Rayleigh Scattering (A), Raman Stokes Scattering (B) and Raman Anti-Stokes Scattering (C) Energy Level Diagram.

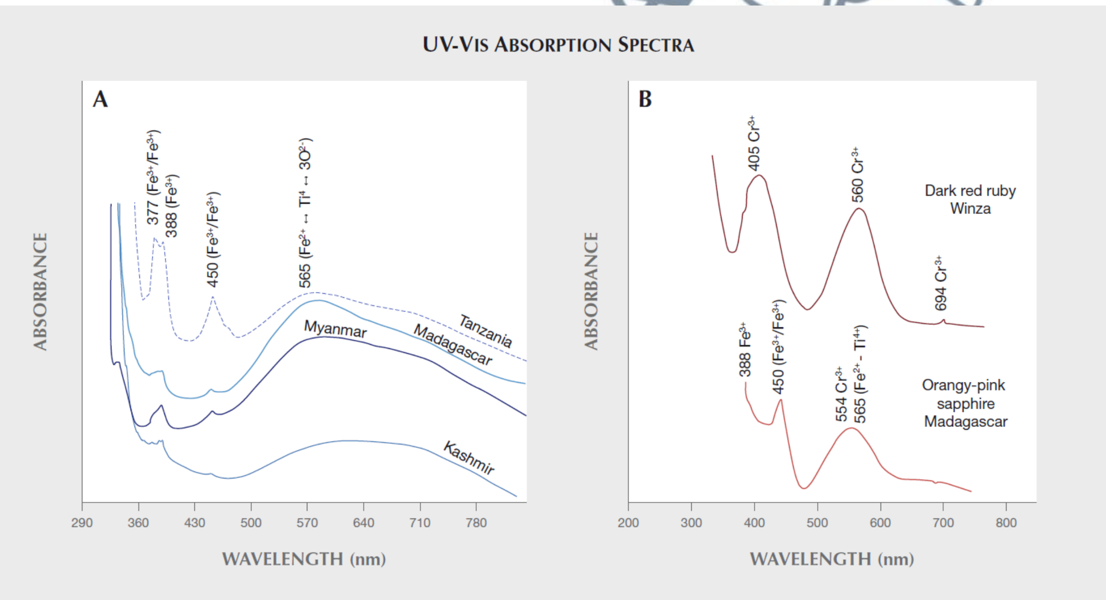


Source: Groat et al. (2019)

Figure 2.28 Confocal Raman Spectroscopy Used to Analyze Inclusions in Gemstones.

Furthermore, spectroscopy includes the examination of spectroscopic signatures of gemstones under ultraviolet, visible, and infrared light. From the information obtained, the geological formation and treatment history of the gemstones can be retrieved. Several types of spectroscopy tools are used to study the chemical properties of gemstones and identify the agents that determine their color. The ultraviolet–visible–near-infrared (UV–vis–NIR) spectroscopy technique analyzes the white light passing through gemstones. The absorption of the white light passing through the stone is measured in ultraviolet–visible–near-infrared regions. In Figure 2.29 (A), the graph of absorption spectrum shows that the iron chromophores (Fe^{3+}) in sapphire from Tanzania show a higher absorption spectrum compared to the sapphire from Kashmir. Meanwhile in Figure 2.29 (B), the dark red ruby from Winza shows a higher absorption spectrum of chromium (Cr3+) chromophores compared to the orangey-pink sapphire from

Madagascar. The absorption features (Figure 2.29) determine the origin of the gemstones as the chromophores can be identified (Groat et al., 2019; Palke et al., 2019b, 2019a; Saeseaw et al., 2019). In addition, Fourier-transform infrared (FTIR) spectroscopy is a type of vibrational spectroscopy that is based on a material's infrared reflectance, transmittance, and absorbance. Gemstones absorb the incident light according to the vibrational frequencies of the bonds present in them (Groat et al., 2019).

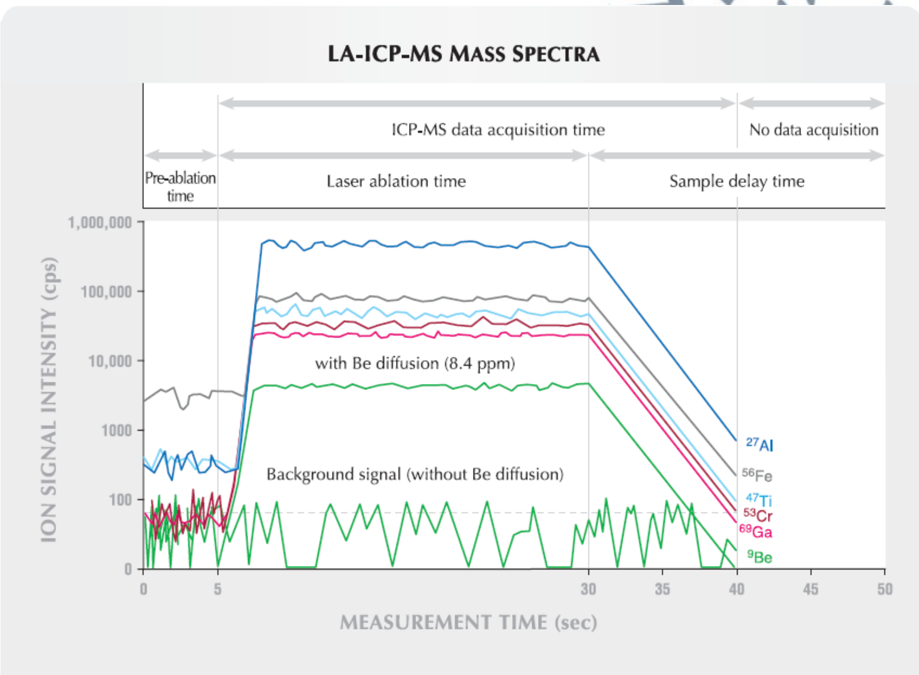


Source: Groat et al. (2019)

Figure 2.29 UV-Vis Absorption Spectra for Sapphire (A) and Ruby (B).

Energy-dispersive X-ray fluorescence spectroscopy (EDXRF) is based on a fact that every gemstone has a different atomic structure. The X-rays interact with a gemstone to capture its atomic structure. Unique sets of peaks are observed in the emission spectrum, which are compared with the reference data to match the information. This technique, however, needs to be performed together with the quantitative corrections. The result may not be sufficiently accurate due to the X-ray absorption and overlapping X-ray emission peaks (Groat et al., 2019). Another related technique is the electron probe microanalyzer. This technique needs the sample to be placed in a high vacuum condition, and then, electrons are beamed into the sample. The result from this technique will show the X-ray characteristics of the sample. The X-absorption energy of the sample will be compared to a sample with known composition and require quantitative corrections. This technique is not a standard gemological laboratory tool because it requires a special sample holder for each sample that must be customized. Moreover, electron microprobes are also very expensive to purchase, maintain, and operate and are not very useful to identify trace elements in rubies and other corundum (Groat et al., 2019).

Laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) detects elements from Be to U at ppm to ppb levels simultaneously. The sample is ablated using UV light, and aerosols are generated from the sample's surface. The elemental and isotopic analysis is done using a mass analyzer. The mass spectra obtained from this technique will show the spectrum of each element in the corundum, as shown in Figure 2.30. However, false elevated levels can occur as the species with masses similar to the element of interest can be detected. This technique also needs to be used with magnification tools to observe ablation pits that usually have diameter in microns. LA-ICP-MS is also unable to separate some close-in-mass interferences (Groat et al., 2019). Due to the limitations of LA-ICP-MS, secondary ion mass spectrometry (SIMS) has been developed. SIMS can have massive sensitivity and high mass resolution. SIMS generates, collects, and analyses secondary ions by beaming sputtering primary ions onto a sample's surface. Unfortunately, SIMS is excessively expensive and requires highly trained technicians and facilities to operate. Furthermore, this technique is slow and has strict sample requirements. Due to these limitations, all materials cannot be analyzed using this technique (Groat et al., 2019).



Source: Abduriyim & Kitawaki (2006)

Figure 2.30 Mass Spectra Obtained using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry to Detect Traces of Elements in Corundum.

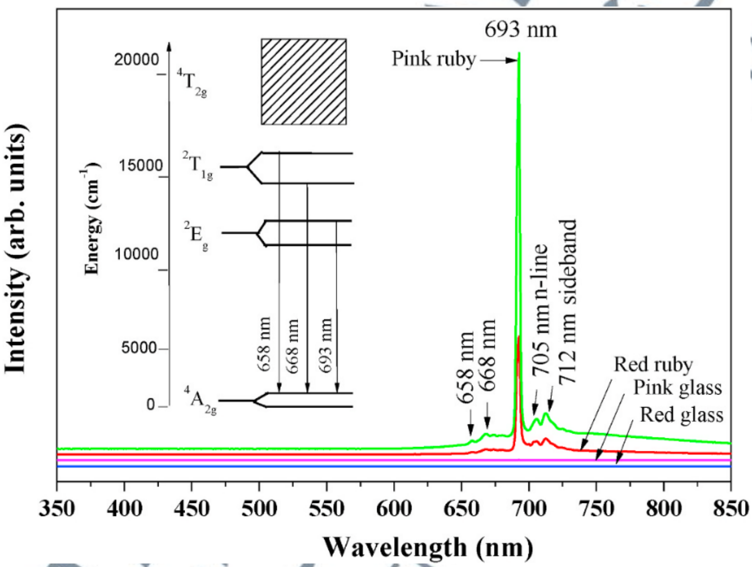
In previous studies, several methods have been used to evaluate the grading of ruby stones. One of them used microscopic tools, which are operated by experienced and expert gemologists for examining rubies (Mukherjee, 2012). Because the previous method is prone to human error, more advanced techniques such as Raman and photoluminescence (PL) spectroscopy were developed to identify the color change of gemstones, yielding more accurate and reliable results (Laurs, 2016). A grading technique involving the X-ray microcomputed tomography (CT) scans was also proposed by Tariwong et al. (2020), where the inner part of rubies is analyzed.

Furthermore, numerous researchers developed more advanced tools for determining the grading valuation of gemstones. As one of the most valuable gemstones, rubies need to be evaluated accordingly based on their carat, cut, color, and clarity. Except the carat, gemologists find it difficult to determine the other three criteria for verifying the quality and value of rubies. The following studies emphasize the importance of grading rubies based on their clarity.

The clarity of different can be determined by photographing them in a fixed environment. As a result, the clarity was assessed using the captured image. In other works, researchers investigated the colour and composition of various rubies (Aung & Zin, 2017). The cut quality of gemstones was investigated by Ekwongmunkong et al. (2016), who proposed an image-processing algorithm for analyzing the cut quality of gemstones.

In 2016, Sahoo et al. examined natural and treated rubies using an electron probe microanalyzer and an X-ray micro-CT scan. From the analysis, the elemental composition of rubies, i.e., ores and minerals, was detected and thereby natural and treated rubies could be identified based on the data produced. Furthermore, Tariwong et al. (2020) proposed that the X-ray-induced luminescence technique can be used to distinguish between natural and fake rubies. To confirm the distinction between natural and imitation stones, optical, compositional, and structural features were investigated.

Other than detecting the elemental composition of rubies, the technique also analyzes the absorption spectra of natural rubies, as displayed in Figure 2.31. Meanwhile, absorption spectra of the imitation rubies cannot be observed, allowing the quick separation of natural and imitation rubies (Tariwong et al., 2020).



Source: Tariwong et al. (2020)

Figure 2.31 X-Ray-Induced Luminescence Spectra of Natural and Synthetic Rubies.

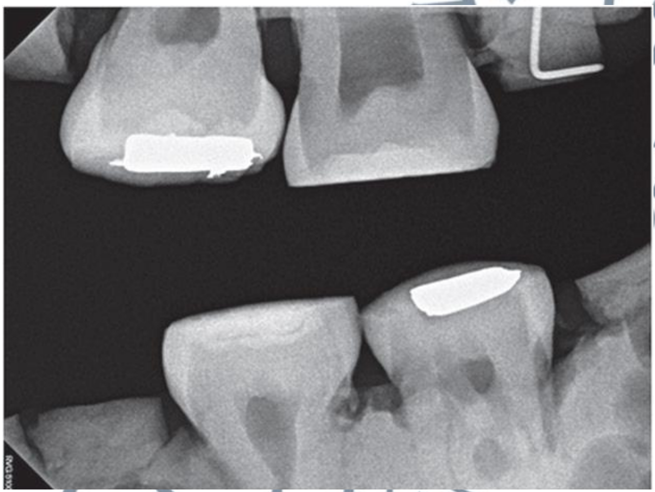
Previous reports show various grading techniques that can identify gemstones' grades and value. In this research, the grades and value of rubies are identified using tomography method. The CCD system selected is highly sensitive to light, which can help in studying the light distribution in rubies. This is a better method than the methods proposed in the previous studies as the CCD linear sensor system provides quantitative analysis technique which results in the low probability of an error occurring, and the method does not disturb the internal environment of the rubies, so the physical and chemical structure of the rubies are preserved. The CCD system has been proven to precisely detect light distribution, which makes the result more accurate (Jamaludin, et al., 2016).

2.4 Charge-coupled Device

CCDs have been the most popular high-performance imaging detectors in all scientific and industrial imaging applications since the 1980s. Boyle and Smith of Bell Laboratories invented CCDs (Sony Corporation, n.d.). Despite that high gains are achieved using complementary metal-oxide-semiconductor (CMOS) imager due to modern silicon processing techniques, CCD imagers remain a significant component of the detector market, particularly for high-end applications (Lesser, 2019).

2.4.1 Architecture of CCD

CCD sensors are a high-demand dynamic electronic component in today's industries. This type of sensor is known for its architectural design because it comprises thousands of tiny sensors that are extremely sensitive to light sources (Jamaludin et al., 2020). Its broad spectral response, huge dynamic range, high sensitivity, low power consumption, shock tolerance, and anti-electromagnetic interference properties facilitated its widespread use in optical imaging, target tracking, and other devices. Because of their distinct properties, CCDs are used as basic imager components in resource, ocean, and meteorological satellites (Yang et al., 2016; Mohd Rahalim et al., 2022).

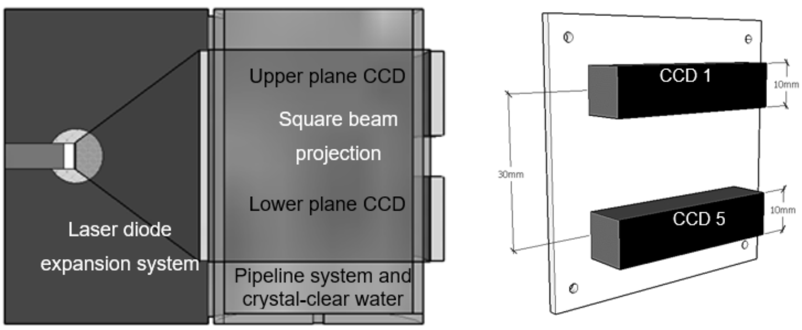


Source: Francio et al. (2018)

Figure 2.32 X-Ray Tomographic Images of Human Teeth Captured by CCD.

CCDs are also used in medical equipment like X-ray tomography scanners. Image reconstructions utilizing X-ray tomography equipment have extremely high resolution, as illustrated in Figure 2.32, which is critical in the medical sector since clear and precise images are required (Kumari & Khare, 2013). CCD tomography systems are currently widely utilized in the processing industry for plant control because they provide a nonintrusive and noninvasive inspection tool (Haff & Toyofuku, 2008). CCD sensors are also resistant to electrical noise and interference, as well as having a high resolution and working speed (Lesser, 2019).

Extensive publications on the analysis and monitoring of multiphase flow have been published (Jamaludin et al., 2016; Jamaludin et al., 2018) solid contamination technology (Jamaludin et al., 2020), sewerage blockage (Jamaludin et al., 2021), and object measurement using CCD tomography systems. Figure 2.33 illustrates a CCD system for detecting sewerage blockage in a pipeline system from previous research conducted by Jamaludin et al (2021).



Source: Jamaludin et al. (2021)

Figure 2.33 Illustration of a CCD System to Detect Sewerage Blockage in Pipeline System.

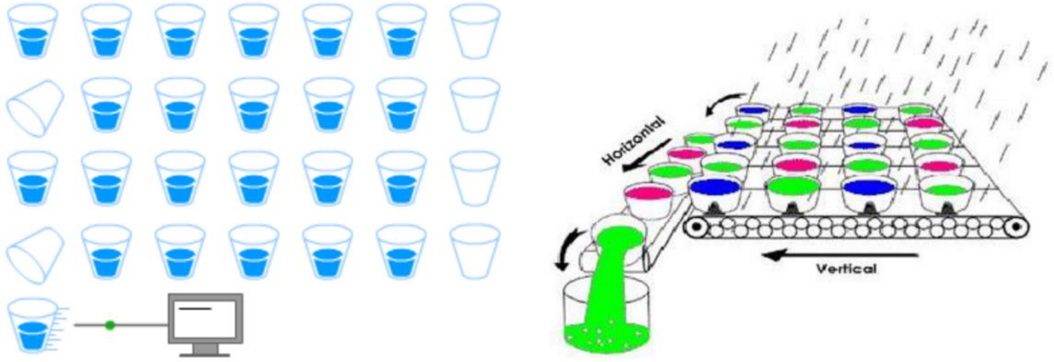
A CCD is a type of image detector that consists of an array of pixels that generate potential wells in response to clock signals, allowing for the storage and transmission of charge packets. The majority of charge packets in a CCD are composed of electrons created by incoming photons or the internal dark signal. Gate structures on the silicon surface define these pixels. A precise time-varying voltage sequence is applied to these gates, physically moving the charge to a charge-to-voltage converter output amplifier. The voltage output sequence is converted into a two-dimensional (2D) digital image by external electronics (usually a computer) (Lesser, 2019).

Although the CCD's initial promise as a memory element has gone, its ability to detect light has secured its place as the industry's standard image sensor technology. Its exceptional light sensitivity was examined for imaging applications, resulting in a massive revolution, most notably in astronomy (Ramli et al., 2011). CCD sensors are classified into two types: linear CCD sensors, which are less expensive and read very quickly, and array CCD sensors, which are commonly used in scientific and high-end imaging (Dominec, 2010; Lesser, 2019).

The basic idea of CCD sensors is based on the movement of electrical charges. A metal oxide–semiconductor (MOS) capacitor serves as the sensor in CCDs. Photons strike electrons as light reaches the CCD's surface, pushing them to leave their covalent band (Jamaludin, 2016).

The number of electrons created is proportional to the number of photons going through the glass of the detector. The electrons produced are then transmitted to the next sensor until they reach the last sensor.

The last sensor sends data to a computer, which analyses it and reconstructs an image (Jamaludin et al., 2015). As the number of incident photons increases, the number of electrons generated also increases (Jamaludin et al., 2015). The illustration of data transfer in CCDs, both monochromatic and color, is depicted in Figure 2.34 below.



Source: Jamaludin (2016)

Figure 2.34 Illustration of the Data Transfer Process in Monochromatic (Left) and Color CCDs (Right).

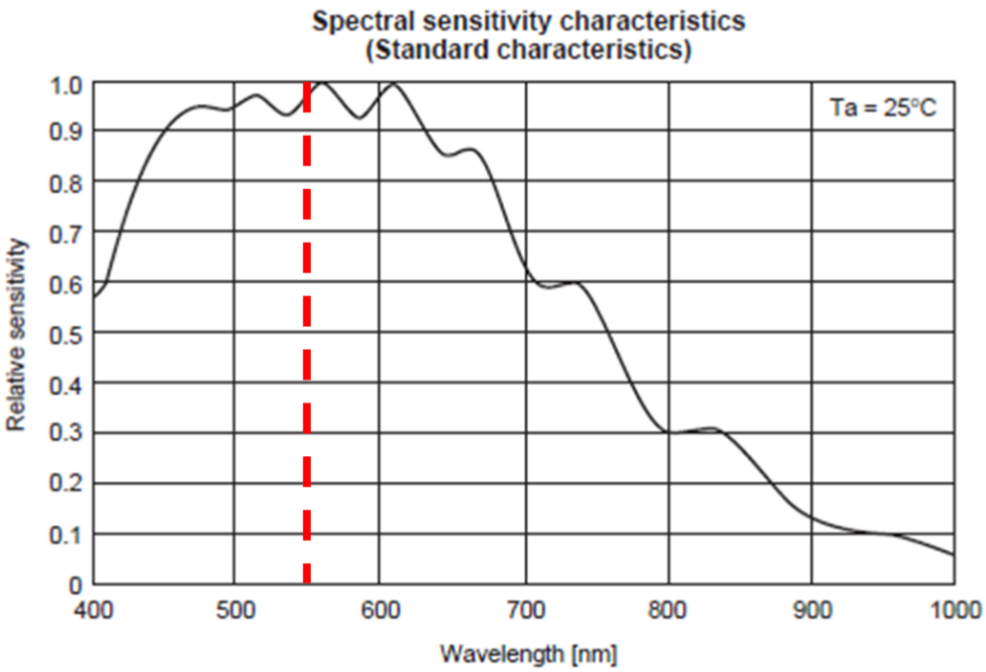
The CCD sensor is unique in terms of the configuration of its architecture, with more than one thousand very thin, light-sensitive pixels. The pixel sizes of the CCD sensor are measured in micrometers. This sensor type provides lower noise, higher sensitivity light detection, and higher-resolution interference compared to CMOS. The receiver is highly sensitive to dark environments. This sensor is uniquely designed to offer a high data resolution using a single line or array of CCDs. The CMOS with a small pixel size originates from the same family as CCD sensors. The primary distinction between a CMOS and CCD is the addition of an analog-to-digital converter in the former (Jamaludin, 2016).

Several varieties of CCD sensors have been developed, each with its unique function that can be used in a certain application. It is often less expensive for process industry applications and comes in two varieties: color and monochromatic CCD sensors. Color CCD sensors are found in video and digital cameras, while monochrome sensors are found in fax machines and scanners. In 1991, researchers discovered a defect in the color scheme of a CCD linear sensor. This is caused by the hassle of scanning three times for three different hues (Jamaludin et al., 2015). Thus, color CCD linear sensor output signals require a significant amount of memory.

Figure 2.35 CCD ILX551A (Left) and CCD ILX511 (Right).

Different varieties of monochromatic CCD sensors, each with a particular purpose, can be used in various applications. CCD ILX551 and CCD ILX551A, for example, are monochromatic CCD sensors. Figure 2.35 depicts the CCD sensors ILX551A and ILX511. CCD ILX551 has the most similar characteristic to CCD ILX551A. Above all, the CCD ILX511 is intended for use in bar code point-of-sale (POS) hand scanners and optical measuring equipment when great accuracy is not required (Sony Corporation, 2004). Meanwhile, the CCD ILX551A is designed for use in facsimile, image scanners, and optical character recognition (OCR) applications that require greater precision and efficiency (Sony Corporation, n.d.).

Figure 2.36 shows the spectral sensitivity characteristic of CCD sensors. In the figure, it can be concluded that the relative sensitivity of the CCD is >0.8 and the light wavelength range is 430–650 nm, which falls within the relative sensitivity value (Jamaludin, 2016; Sony Corporation, n.d.). Rubies show absorption at 550 nm, i.e., visible light. It has a relative sensitivity of >0.9, represented by red dotted lines in Figure 2.36. As a result, CCDs can be used to detect the features of light distribution in ruby stones. Table 2.2 shows the comparison between two types of CCDs: CCD ILX551A and ILX511.



Source: Sony Corporation (n.d.)

Figure 2.36 Spectral Sensitivity Characteristics of CCD Sensors.

Table 2.2 Comparison between CCD ILX551A and ILX511 Sensors.

ILX551A - 2048-pixel CCD Linear Sensor (B/W)	**ILX511 - 2048-pixel CCD Linear Image Sensor (B/W)**
Description The ILX551A is a reduction-type CCD linear sensor intended for use in facsimile, image scanner, and OCR applications. This sensor reads documents in B4 format at a density of 200DPI (Dot Per Inch). For ease of use, a built-in timing generator and clock drivers ensure direct drive at 5V logic.	**Description** The ILX511 is a rectangular reduction type CCD linear image sensor designed for bar code POS (point-of-sale) hand scanner and optical measuring equipment use. A built-in timing generator and clock-drivers ensure single 5 V power supply for easy use.
Features • Number of effective pixels: 2048 pixels • Pixel size: 14µm x 14µm (14µm pitch) • Built-in timing generator and clock-drivers • Ultra-low lag • Maximum clock frequency: 5MHz	**Features** • Number of effective pixels: 2048 pixels • Pixel size: 14 µm x 200 µm (14 µm pitch) • Single 5 V power supply • Ultra-high sensitivity • Built-in timing generator and clock-drivers • Built-in sample-and-hold circuit • Maximum clock frequency: 2MHz
Absolute Maximum Ratings • Supply voltage VDD1: 11 V VDD2: 6 V • Operating temperature –10 to +55 °C • Storage temperature –30 to +80 °C	**Absolute Maximum Ratings** • Supply voltage VDD: 6 V • Operating temperature: –10 to +60 °C • Storage temperature: –30 to +80 °C

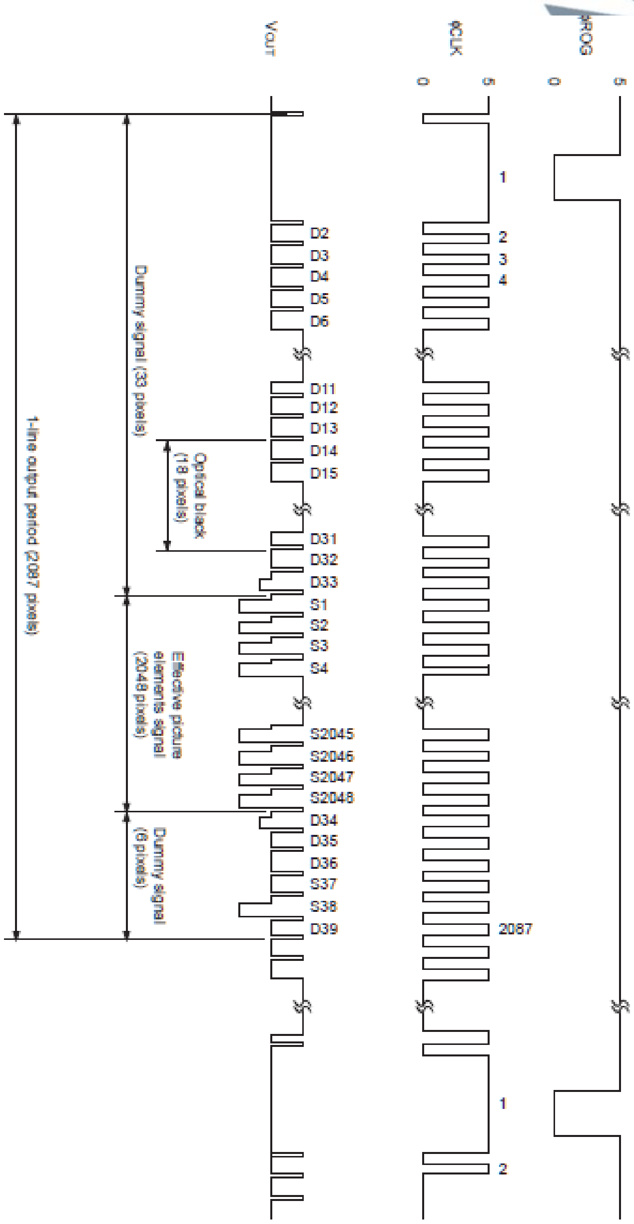
Table 2.2 continued

ILX551A - 2048-pixel CCD Linear Sensor (B/W)	**ILX511 - 2048-pixel CCD Linear Image Sensor (B/W)**
Recommended Voltage VDD1: 8.5V < 9.0V < 9.5V VDD2: 4.75V < 5.0V < 5.25V	**Recommended Voltage** VDD: 4.5V < 5.0V < 5.5V
Input Capacity of Pins CLK pin: 10pF ROG pin: 10pF	**Input Capacity of Pins** CLK pin: 10pF
Saturation Output Voltage Vsat: 1.5V ~ 1.8V	**Saturation Output Voltage** Vsat: 0.6V ~ 0.8V
***Photo Response Non-Uniformity (PRNU)** PRNU = $\frac{(Vmax-Vmin)/2}{Vave}\ x\ 100\%$ The maximum output is set to VMAX, the minimum output to VMIN and the average output to VAVE.	***Photo Response Non-Uniformity (PRNU)** PRNU = $\frac{(Vmax-Vmin)/2}{Vave}\ x\ 100\%$ The maximum output is set to VMAX, the minimum output to VMIN and the average output to VAVE.

Source: Sony Corporation (n.d.)

Based on the data in the table above, it is clear that the CCD ILX551A sensor outperforms the CCD ILX511. Aside from having the same number of effective pixels, the CCD ILX551A sensor has a 14-m 14-m pixel area, which is smaller than the CCD ILX511 sensor. This demonstrates that the CCD ILX551A sensor is more accurate than the other CCD sensor. Furthermore, both CCD sensors are efficient, but the CCD

ILX551A sensor has a higher maximum frequency of 5 MHz than the CCD ILX511 sensor, which has a maximum frequency of 2 MHz. This enables the CCD ILX551A sensor to send and receive more data in a shorter period.



Source: Sony Corporation (n.d.)

Figure 2.37 Clock Timing Diagram of the CCD ILX551A Sensor.

As shown in Figure 2.37, the Sony ILX551A linear CCD sensor requires two input signals: the readout gate (ROG) and clock signals. The ROG signal aids in activating the end of each frame. The Sony CCD ILX551A sensor has 2048 sensitive pixels. According to the datasheet, dummy signals would be present at the beginning and end of each image clock in each frame. A dummy signal is used as a backup for other pixels in this CCD sensor. There are a total of 2087 signals for this sensor including the dummy signals. The CCD ILX551A sensor requires the ROG signal, whereas the CCD ILX511 sensor does not require this signal (Sony Corporation, n.d., 2004). Without the ROG signal, it is hard for the user to capture the data, as there is no end activated for each frame. Thus, the data will be fed continuously into the system.

To improve the CCD's performance, researchers investigated a variety of criteria. In general, seven criteria should be considered for investigating the CCD's performance. The requirements include quantum efficiency (QE), signal to noise ratio, spectrum sensitivity, transfer efficiency, spatial resolution, blooming, and dark current. CCD sensors have a large QE fraction, ranging from 40% to 90% (Buil, 1991), in comparison to other optoelectronic sensors. CCD sensors typically can detect a light wavelength range of 400–1000 nm, which encompasses visible and infrared regions (NASA, 2016). CCD sensors are now available in a number of sizes, each with a distinct amount of spatial resolution. When a CCD sensor is exposed to high-intensity light sources or excessive lighting, blooming can develop. Dark current is another factor that influences CCD performance. Even if the sensor is positioned in a dark region, when the signal is gathered, some dark current will flow (Buil, 1991). The criteria for a CCD sensor are as follows:

- Quantum efficiency (QE)

    - The quantum efficiency is defined as the ratio of the number of photons emitted by the phosphor to the number of photons absorbed (Srivastava, 2003). A CCD sensor has a high QE of 40%–90% compared to other optoelectronic sensors. Thus, it can be considered the best detector (Jamaludin, 2016).

- Spectral sensitivity

    - A CCD sensor can detect a range of light wavelengths from 400 to 1000 nm. This range of wavelength is called spectral sensitivity (Jamaludin, 2016).

- Transfer efficiency

    - When an electron is being transferred from one pixel to another, the transfer process is measured. This transfer process is known as transfer efficiency (Jamaludin, 2016). Temperature, charge trapping, a tiny amount of charges in one pixel, and switching can all affect the transfer process (Jamaludin, 2016).

- Spatial resolution

    - The smaller the size of the pixel is, the higher the image resolution is (Jamaludin, 2016).

- Blooming

    - Blooming is the process in which a large number of electrons are produced in a single pixel, and excess electrons remain after the transfer process. This can happen if CCD sensors are exposed to excessively bright light sources or strong illumination (saturation occurs when CCD sensors are subjected to high-intensity light for a long period of time.) (Jamaludin, 2016).

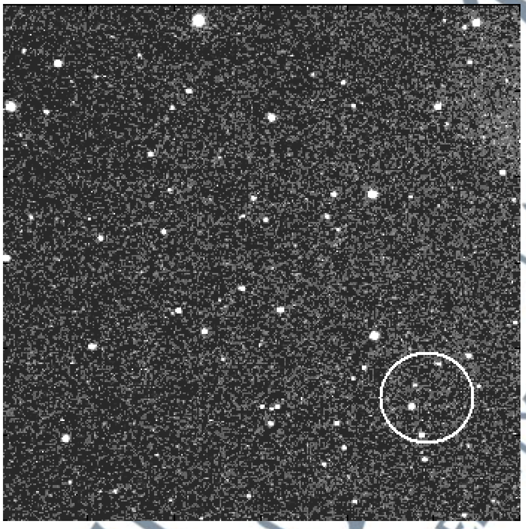
- Dark current

    - When a signal is detected despite the sensor being positioned in a dark location, this is referred to as dark current. Dark currents are usually caused by the effect of the surrounding temperature (Jamaludin, 2016).

2.4.2 Applications of CCD Sensors

Smith and Boyle, the inventors of CCD sensors, used CCDs in solid-state cameras at an early point in their development from 1970 to 1975 (Jamaludin et al., 2015; Zhou et al., 2011). These CCDs were also used in television broadcasting (Jamaludin et al., 2015). In 1983, these sensors were used for the first time in astronomy. Several significant companies then began to manufacture this type of sensor to fulfil the needs of astronomy technology (Yang et al., 2016).

CCD cameras used in astronomy are generally pricey. To obtain astronomical photographs, astronomical engineers often employ arrays of CCD sensors. On a 6 inches wafer is mounted the largest CCD sensor ever recorded (Jamaludin et al., 2015). This application explains the basic concept of detecting an item using a CCD sensor.



Source: Suszynski (2009)

Figure 2.38 Image of Stars Captured by the CCD Sensors.

Arrays of CCDs, for example, are used in astronomy to detect stars, planets, and meteors from millions of miles away using light reflection. As a result, the goal is to identify a brilliant light spot on a dark background in an unrevealed region. This is how the presence of stars are detected using CCD sensors, as shown in Figure 2.38 (Jamaludin et al., 2015). CCD sensors became popular in the photographic industry in 1991. Numerous models of digital cameras have used the CCD technology to produce high-resolution images.

The cost of a CCD sensor in a digital camera is cheaper than that of a CCD sensor in a telescope. Additionally, because pixel characteristics and sizes depend on customer preferences, they change accordingly (Jamaludin et al., 2015). CCD technology enables a compact, high-quality image, and perhaps even more efficient camera (Zhou et al., 2011).

In terms of low noise, low power, and large size, modern X-ray astronomy detection systems have progressive advancement. The X-ray CCD offers a wide range of applications in the field of X-ray astronomy since it outperforms typical high-energy particle detectors in terms of energy and spatial resolution (Mehta et al., 2015). CCD technology is also employed in X-ray CT scans. X-ray CT is one of the most effective nondestructive testing technologies for thoroughly studying an object since it offers morphological and physical information on the internal structure of the studied sample. Furthermore, CCD cameras are combined with other components to generate digital radiography for X-rays, such as a CCD camera linked with a taper for micro-CT, a CCD camera linked with a fan of coherent optical fibre ribbons (multislice linear detector), and a scintillating screen viewed by a CCD camera (cone-beam CT) (Lu et al., 2018).

Recent advances in CCD-based optical CT scanners have enabled speedy and cost-effective three-dimensional (3D) gel dosimetry in current radiation applications. CCD-based optical CT can receive the entire plane of data at each step, allowing for quick 3D dosage distribution (Morigi et al., 2010). The CCD laser range scanner (CCD-LRS) technique is also developed, and it is capable of storing geometric and colour data, which increases scanning and tracking accuracy (Chang, 2015). CCD scanners, like MRI scanners, are widely employed in the medical field (Pheiffer et al., 2012).

The most common applications of CCD sensors are optical displacement sensors (Jamaludin et al., 2015; Ni et al., 2009; Zhou et al., 2011), surface detection sensors (Jamaludin et al., 2015). Thickness detection sensors (Li et al., 2004), and object detection systems (Jamaludin et al., 2020). Because CCD cameras have great precision for measuring 2D pictures and lasers have fantastic precision in the axial direction, Fei et al. (2010) discovered that the optimal combination is laser and CCD cameras.

The combination of CCD and laser, according to Ni et al. (2009), has contributed in the development of thickness-detecting sensors with high sensitivity, exact accuracy, and constant reading distance. As a result, CCD and laser-diode transceivers have shown to be the perfect transceivers for opaque object measurement techniques. Transparent items may allow more light to pass through than solid objects.

Since CCD sensors cannot differentiate light intensities with very small differences, the detection of transparent object might be problematic. Jamaludin et al. developed the optical tomography (OPT) device, which analyses the movement of air bubbles in ionic crystal-clear water (2016). With minimal opacities, this CCD tomography device can reconstruct a cross-section image of a moving object in crystal-clear water (Jamaludin et al., 2016; Jamaludin et al., 2017).

2.4.3 Application of CCD Sensors in Gemstones

Gemology is the scientific study of gemstones. Archaeologists, art historians, conservators, mineralogists, gemstone merchants, amateur and professional gemologists all face a difficult task. They must understand not only the fundamentals of many sciences (mineralogy, crystallography, geology, chemistry, physics, and, in some circumstances, biology), but also economic considerations (Karampelas et al., 2020). The study of gemstones begins with determining their chemical composition, then determining if they are natural or manufactured (i.e., imitation or synthetic), testing for enhancing treatments, grading, and, in some cases, determining their geographic origin.

Furthermore, all data should be obtained nondestructively and noninvasively. When such stones are placed in jewels or artworks, their analysis becomes more difficult. Because of the high value of gemstones and jewels, it is frequently impossible to extract them without causing damage, especially during the testing procedure. As a result, such jewels will require on-site identification techniques. As a result, gemologists in charge of the stones must be professionally trained in the various ways of identification while paying close attention to all of the aforementioned situations and requirements (Karampelas et al., 2020).

This research will focus on analyzing the ruby's clarity without disturbing the internal or external conditions of the ruby. The analysis will use the characteristic of light distribution in rubies, which involves light reflectance and absorption. Because the CCD linear sensor is a sensor that mainly focuses on detecting these two characteristics, the analysis of the clarity of ruby using the CCD sensor is possible.

It is believed that this specific approach will produce a quantitative and standardized grading technique based on the voltage produced by the CCD sensor.

2.5 Laser

Lasers cause atoms or molecules to emit light at specified wavelengths, which is then amplified to produce a very narrow beam of radiation. The emission typically spans a very narrow spectrum of visible, infrared, and ultraviolet wavelengths. A laser is a light-emitting device that uses optical amplification to stimulate electromagnetic emission. The term "laser" refers to light amplification by stimulated emission radiation. (Hecht Jeff, 2020).

A laser diode is known as a semiconductor device that generates consistent high-intensity light. The operating power of a laser diode is less compared to other light-emitting devices. Aside from that, a laser diode is typically small, allowing better handling. Furthermore, laser diodes produce high-efficiency light. A laser light emitted by a laser diode has coherent, monochromatic, bright, and directional properties. Coherence is an essential laser property due to stimulated emissions. The phase of the emitted light waves is the same. In comparison, in the case of an ordinary LED light source, the property of coherence does not exists because of the spontaneous photon emission process (Circuit Globe, 2011).

Laser light is monochromatic. In particular, it has one wavelength and is monochrome in nature. Light waves with a single wavelength indicate a single color of the emitted radiation. Fundamentally, the light brightness is determined by the power per unit surface per unit solid angle. Laser diodes produce high-intensity and more power light due to continuous reflections. This enables bright light to be generated by the device. Further, laser light is highly directional, as there is no divergence of the light from a laser diode. The directionality in a laser diode is achieved using multiple mirror reflections of the emitted photons. The light will be skipped every time it deviates from its axis, resulting in only a highly concentrated light beam being achieved (Circuit Globe, 2011).

In many trades, such as construction, installation, surveying, and listing, lasers are used. Vertical line, horizontal line, and sometimes both vertical and horizontal lines are projected for fast and easy accurate long-range measurements. Red lasers are used to be the common laser that are applied in the industries. However, they appear to have fallen to the bottom ever since green lasers came along and technology developed. Red lasers still offer exact accuracy; thus, the laser to be selected depends on the application.

Red lasers are not as diverse as green lasers, but a laser detector can be utilized to improve and expand the red lasers. Most receivers detect only red light, which indicates that they do not work with green lasers (Katy, 2021). Red lasers have a wavelength of 620–700 nm (Haigh, 2020).

When Cr substitutes Al in corundum, the Cr atoms absorb some light wavelengths. This is reflected through the appearance of red light. This mirrored red light provides the eyes with red color characteristics (K. Nassau, 1997). Rubies also show an absorption at 550 nm (Eaton-Magaña et al., 2017).

In the research conducted by Eaton-Magaña & Breeding (2016), a laser is used as the energy source for photoluminescence (PL) measurements. The laser observation revealed several general characteristics, such as prominent diagnostic peaks in spectra, and occasionally, underlying broad bands (Eaton-Magaña & Breeding, 2016). In gemology, laser characteristics are used to determine if a diamond has been treated and are of natural or synthetic origin. Furthermore, the laser can be used to determine the origin of color of coral and the separation of natural, manufactured, or heat-treated spinel. The laser's advantages of very sensitive measurements for faults at low concentrations aid the gemologist in gemstone analysis.

2.6 Summary

This chapter involves discussion on four main sections. The first section on the precious stones specifically on the ruby stone. This includes the grading criteria of ruby stones, types of inclusions in ruby, types of rubies and the optical and physical characteristic of rubies. The following section are the reviews on the gemology tools and also the techniques utilized by the previous researchers to analyze rubies. The Table 2.3 below show the summary of the techniques used by the gemmologist and the previous researchers. Finally, the next two section discusses briefly on the CCD linear sensor and laser respectively.

Table 2.3 Summary of Gemology Tools and Techniques.

Tool / Techniques	Limitation of the Study	CCD Linear Sensor System
Loupe	- Depends highly on human vision - Require skills to operate Source: Clark (n.d.)	- Affordable - Quantitative - Portable - Accurate - Simple & Easy to use (does not require skills) Source: Sony Corporation (n.d.) & Jamaludin (2016)
Microscope, refractometer, dichroscope, polariscope, spectroscope	- Expensive - Depends highly on human vision - Require skills to operate - Not portable (need to be done in the laboratory) Source: Fritsch & Rondeau (2009); Clark (n.d); Liao et al. (2016)	
Raman spectroscopy	- Require microscopy technique - Require skills to operate - Limited to stones with certain amount of fluorescence Source: Palke et al. (2019a0; Wang et al. (2019)	

Table 2.3 continued

Tool / Techniques	Limitation of the Study	CCD Linear Sensor System
Ultraviolet–visible–near-infrared (UV–vis–NIR) spectroscopy	- Expensive - Require skills to operate and set up - Very sensitive to electronic noise and light (may reduce it accuracy) Source: Groat et al. (2019); Palke et al. (2019b & 2019a); Saeseaw et al. (2019)	- Affordable - Quantitative - Portable - Accurate - Simple & Easy to use (does not require skills) Source: Sony Corporation (n.d.) & Jamaludin (2016)
Fourier-transform infrared (FTIR)	- Expensive - Require skills to operate - Limited to stones with certain amount of infrared absorption Source: Groat et al. (2019)	

In the next chapter, the red laser is used in the experiment. The proposed system will be tested with the laser in ON and OFF conditions in the presence and absence of a ruby. The analysis of each condition is completed when the CCD captures the light intensity from the laser and ruby.