LAB-GROWN COLORED DIAMONDS FROM CHATHAM CREATED GEMS

James E. Shigley, Shane F. McClure, Christopher M. Breeding,
Andy Hsi-tien Shen, and Samuel M. Muhlmeister

Synthetic colored diamonds (yellow, blue, green, and pink) from a new source in Asia are now being sold by Chatham Created Gems of San Francisco, California. Some of this new material displays hues and weaker saturations that more closely resemble natural diamonds than most of the synthetic diamonds we have encountered previously, which typically had very intense colors. These as-grown and treated type I and type II synthetic diamonds, produced by a high pressure/high temperature process, have many distinctive visual and spectroscopic features that serve to separate them from natural diamonds. These include geometric patterns of color zoning and luminescence, metallic inclusions, and bands seen in the visible and photoluminescence spectra.

One of the most important gemological developments in recent years has been the commercial availability of jewelry-quality synthetic diamonds. What for almost three decades was primarily an industrial or research product is now becoming a commodity in the gem and jewelry marketplace. In addition to the products being offered by such companies as the Gemesis Corp. and Lucent Diamonds, Chatham Created Gems of San Francisco, California, has introduced a line of synthetic diamonds from a new source (figure 1). This article presents results of our examination of a large group of these high pressure/high temperature (HPHT) laboratory-grown diamonds in yellow, blue, green, and pink colors showing a full range of saturation, from weak to strong. Our examination indicates that most of the yellows and blues represent "as-grown" colors (i.e., those produced by nitrogen and boron impurities during diamond crystallization), while the greens and pinks are the result of either growth or growth plus post-growth treatment processes (i.e., irradiation, with or without subsequent heating).

A single manufacturer is supplying Chatham Created Gems with approximately 500 carats of synthetic diamond crystals per month, with future increases in production planned (T. Chatham, pers. comm., 2004). The material is faceted in China into cut goods that range from a few points (melee) to as large as 2 ct. Chatham Created Gems is the sole distributor of this material for jewelry purposes. Previous gemological reports on synthetic diamonds produced in Russia and sold by Mr. Chatham (see, e.g., Scarratt et al., 1996) may not be applicable to the new HPHT-grown material described here, which is grown in Asia with a non-BARS press.

This article provides information on material from all four color categories of this new product, including descriptions of green and pink synthetic diamonds, which have not been reported on extensively in the gemological literature. Most of the green samples display this color because they contain both blue and yellow growth sectors. Some of this new material displays hues and weaker saturations that more closely resemble natural diamonds

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Figure 1. A new, undisclosed source is producing a broad range of synthetic diamonds for Chatham Created Gems of San Francisco. The loose faceted yellow, blue, and pink lab-grown diamonds shown here range from 0.28 to 0.51 ct. The jewelry set with pink and blue lab-grown diamonds is by Judith Conway. The ring set with a 1.19 ct yellow lab-grown diamond is by Doris Panos. Courtesy of Chatham Created Gems; photo by Harold & Erica Van Pelt.

than most of the synthetic diamonds we have encountered in the past, which have had very intense colors. Furthermore, a number of the examined samples are very low-nitrogen-containing synthetic diamonds that are nearly type IIa material; past reports on synthetic diamonds that are type IIa described material that was colorless or near colorless (for an explanation of diamond types, see Collins, 1982, 2001). The broad commercial availability of these new synthetic diamonds with lighter, more "natural-looking" colors reinforces the need for gemologists to understand how to identify them.

MATERIALS AND METHODS

We examined a total of 129 samples during this study, selected from a broad range provided by Chatham Created Gems. There were 20 crystals (0.44–1.74 ct) and 109 faceted samples (0.13–1.34 ct). In terms of their basic hues, there were 39 yellow (including one green-yellow and one yellow-brown), 29 blue, 16 green (including one greenish gray), and 45 pink samples (including one pinkish purple), some of which are illustrated in figure 2. (Note that all color terminology is according to the nomenclature used by the GIA Gem Laboratory to describe fancy-color diamonds.) Most of these are

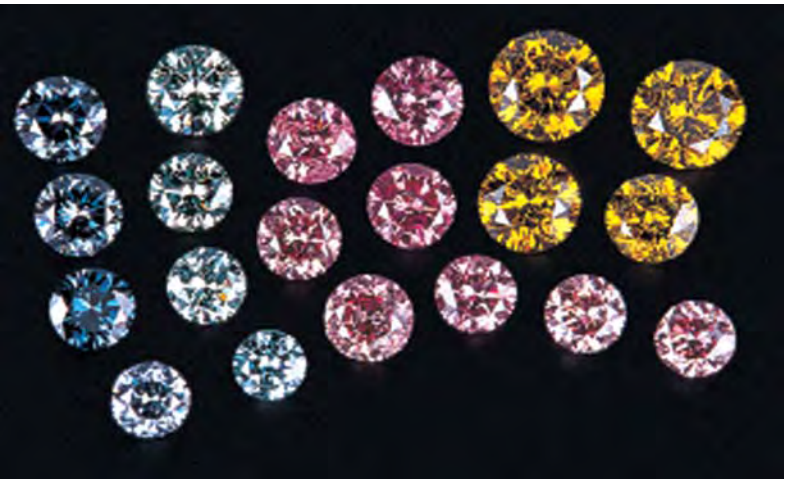


Figure 2. These blue, green, pink, and yellow laboratory-grown faceted diamonds (0.13–1.34 ct) are representative of the faceted material examined for this study. Photo by Maha Tannous.

representative of the product now being sold, although the yellowish green and greenish blue samples currently are not available commercially. The faceted samples exhibited a range of styles, including round brilliant, cut-corner rectangle modified brilliant, and octagon shapes.

Standard gemological properties were obtained on most of these samples. For research purposes only, GIA Gem Laboratory graders assigned equivalent clarity and fancy color grades to these synthetic diamonds (GIA does not issue grading reports on synthetic diamonds). Internal features were observed with a binocular gemological microscope using various illumination techniques. Reactions to UV radiation were viewed in a darkened room with four-watt long- (366 nm) and short-wave (254 nm) Ultraviolet Products lamps. Absorption spectra were observed with a desk-model Beck prism spectroscope. Electrical conductivity was tested for 27 faceted blue samples and eight of the green samples with a gemological conductometer.

Samples from each of the four color groups were selected for more advanced testing. We used a Thermo-Spectronic Unicam UV500 spectrophotometer to record the absorption spectra of 65 samples (13 yellow, 14 blue, 14 green, and 24 pink). Each was held in a cryogenic cell cooled by liquid nitrogen, with the spectrum taken over a range of 250–850 nm at a scan rate of 30 nm/min and a bandwidth of 0.5 nm. Absorption spectra in the mid-infrared range (6000–400 cm^{-1}, with 1 cm^{-1} resolution) were recorded for 98 samples (30 yellow, 23 blue, 15 green, and 30 pink) at room temperature with a Thermo-Nicolet Nexus 670 Fourier-transform infrared (FTIR) spectrometer. Photoluminescence (PL) spectra were recorded with a Renishaw 1000 Raman microspectrometer over a range of 520–1050 nm using a 20 mW 514.5 nm Argon-ion laser; the 61 samples analyzed (14 yellow, 13 blue, 11 green, and 23 pink) were held in a cryogenic cell cooled by liquid nitrogen. Five summed scans were accumulated for each sample to achieve a better signal-to-noise ratio.

Qualitative chemical analyses of 12 samples (2 yellow, 3 blue, 3 green, and 4 pink) were obtained by energy-dispersive X-ray fluorescence (EDXRF) spectroscopy using either of the following two instruments: a Thermo-Noran Omicron system operating at an accelerating voltage of 25 kV with beam currents between 0.6 and 3.2 mA, and a Kevex Spectrace QuanX system operating at an accelerating voltage of 35 kV with a beam current of 0.35 mA.

Room-temperature cathodoluminescence reactions of four samples (one from each color group) were observed with a Luminoscope ELM-3R cathodoluminescence (CL) unit operating at 15 keV and 1.0 mA. The luminescence patterns seen with this CL unit are similar to those that would be observed with the De Beers DiamondView diamond verification instrument (see Welbourn et al., 1996).

RESULTS

The faceted samples varied in clarity from VVS to I (most were VS or SI); their clarity grades were influenced mainly by the number, size, and visibility of metallic inclusions. In some instances, removal of prominent inclusion(s) located near the culet would improve the clarity considerably.

The samples represent various diamond types (as determined by infrared spectroscopy) with different gemological properties. Table 1 summarizes the visible-range absorption bands recorded in the spectra of all four colors of synthetic diamonds, and gives their causes. Table 2 lists the photoluminescence (PL) bands (and their causes) recorded for all four colors of these synthetic diamonds.

Some samples represent as-grown colors produced during crystallization, while others are due to a combination of the growth process and post-growth treatment. Therefore, the four color groups will be described individually to clarify the explanation of their diagnostic features.

Yellow. *Visual Appearance.* All 39 samples in this group were type Ib, and included hues of yellow (2),

brownish orangy yellow (16), orangy yellow (7), orange-yellow (12), and green-yellow (1), as well as one sample that was yellow-brown (figure 3). The eight crystals (0.63–1.74 ct) displayed typical cuboctahedral morphology. In general, they were well developed in shape, with flat faces and sharp corners and junctions between faces; however, some displayed slight distortions due to missing crystal faces or unequal development of faces.

If graded for color, the 31 faceted samples would be described as Fancy (1 sample), Fancy Vivid (8), and Fancy Deep (20).

Features Seen with Magnification. All the crystals and faceted samples exhibited some form of growth sector–related color zoning, which varied from prominent (where colorless zones could be seen) to subtle (lighter and darker yellow zones), as illustrated in figure 4. Such zoning is best observed by immersing the sample in water to minimize surface reflections (figure 5). Since the table facet is usually cut parallel to a cubic crystal face for maximum weight retention, placing a faceted sample table down in water often revealed the cross- or square-shaped color zoning pattern that is characteristic of synthetic diamonds (see, e.g., Shigley et al., 1995). Another way to check for zoning in a faceted sample is to hold the stone between the table and the culet and then rotate it, noting changes in color zones at intervals of 90°.

A number of samples also displayed intersecting patterns of internal graining, often seen as hourglass or funnel-shaped patterns (figure 6). This graining represents the boundaries between growth sectors.

The 31 faceted samples (0.21–1.34 ct) represented a broad range of clarity grades (VVS—3 samples, VS—4, SI—9, and I—15). The low grades were primarily due to the presence of metallic inclusions

TABLE 1. UV-Visible absorption features recorded for the Chatham synthetic diamonds studied.

Wavelength (nm)	Band label	Cause[a]	Yellow		Blue		Green		Pink
			As-grown (11)	Treated (2)	As-grown (13)	Treated (1)	As-grown (8)	Treated (6)	Treated (24)
271		Nitrogen	St[b], Common[c]	St	Wk to Mod, Common	St	St, Common	St	St, Common
393		Irradiation	——[d]	——	——	Wk	——	Mod to St	——
412	GR8	Irradiation	——	——	——	Wk	——	Wk	——
416	GR6	Irradiation	——	——	——	Wk	——	——	Wk, Rare
419	GR5	Irradiation	——	——	——	Wk	——	Wk	——
424	H6	Irradiation + heating	——	——	——	Wk	——	Wk	Wk, Common
429	GR3	Irradiation	——	——	——	Wk	——	Wk	Wk, Rare
442	2.087 eV	Irradiation + heating	——	——	——	——	——	——	Wk, Common
489		Irradiation + heating	——	——	——	Wk	——	Mod	——
494	2.51 eV	Nickel	Wk, Common	Wk	——	——	——	——	——
503	3H	Irradiation	——	——	——	Wk	——	Wk	——
523	NE3	Nickel	——	——	——	——	——	Wk	——
527	2.351 eV	Nickel	——	——	——	——	——	Wk	——
575	NV^0	Irradiation + heating	——	——	——	——	——	——	Wk to St, Common
595	595 nm	Irradiation + heating	——	Wk	——	Mod	——	Wk to Mod	Wk to Mod, Common
637	NV^-	Irradiation + heating	Wk, Common	Wk to St	——	——	——	Wk	Wk to St, Common
647		(Unknown)	——	——	——	——	——	Wk	——
658		Nickel	Wk, Common	Wk	——	——	——	——	——
667		Irradiation	——	——	——	Mod	——	Wk	——
741	GR1	Irradiation	——	Wk to Mod	——	St	——	Mod to St	Wk, Common

[a] *Reference: Zaitsev (2001).*
[b] *Intensity: Wk = weak, Mod = moderate, and St = strong, based on a subjective judgment of peak height.*
[c] *Abundance: Rare = present in less than one-third of samples investigated, Common = present in more than one-third of samples investigated.*
[d] —— *= not present.*

TABLE 2. List of photoluminescence features recorded for the Chatham synthetic diamonds studied.

Wavelength (nm)	Band label	Cause[a]	Yellow		Blue		Green		Pink
			As-grown (12)	Treated (2)	As-grown (12)	Treated (1)	As-grown (6)	Treated (5)	Treated (23)
527	2.351 eV	Nickel	——[b]	Mod	——	Wk	——	Wk	——
530		(Unknown)	——	St	Wk, Rare	Mod	Wk, Rare	Wk to St	——
535		Irradiation + heating	——	Wk	——	Wk	——	Wk	——
546	2.267 eV	Nickel	Wk[c], Common[d]	——	——	Wk	Wk, Rare	——	Wk, Rare
552		(Raman Band—Intrinsic to diamond)	(Common)	(Common)	(Common)	(Common)	(Common)	(Common)	(Common)
559		(Unknown)	Wk, Rare	——	Wk, Rare	Wk	Wk, Common	——	——
562		(Unknown)	——	——	——	Wk	——	——	——
575	NV^0	Irradiation + heating	Wk to Mod, Common	Mod to St	Wk, Common	Mod	Wk to St, Common	Wk to St	St, Common
580		Nickel	Wk, Rare	St	Wk, Common	Wk	Wk, Rare	Wk	——
589		(Raman Band—Intrinsic to diamond)	(Common)	(Common)	(Common)	(Common)	(Common)	(Common)	(Not observed)
596		(Raman Band—Intrinsic to diamond)	(Common)	(Common)	(Common)	(Common)	(Common)	(Common)	(Not observed)
611		(Unknown)	Wk, Common	——	——	——	Wk, rare	——	——
623		Nickel	Wk, Rare	——	——	——	——	——	——
637	NV^-	Nitrogen	Wk to St, Common	St	Wk, Rare	Mod	Wk to St, Common	St	St, Common
647		(Unknown)	——	——	——	St	——	Mod to St	——
657		Nickel	Wk, Common	——	——	——	——	Wk to Mod	——
693		Nickel	Mod to St, Rare	——	——	——	——	——	Mod, Rare
704		Nickel	Wk, Rare	——	——	——	——	——	——
711		Nickel	——	——	——	——	Wk, Rare	——	——
721		Nickel	——	——	——	——	——	Wk to St	——
727		Nickel	Wk to Mod, Rare	——	——	——	——	——	——
732		Nickel	——	Wk	——	——	——	——	——
741	GR1	Irradiation	——	St	——	St	——	Mod to St	——
744	GR1	Irradiation	——	Wk	——	St	——	Wk to Mod	——
800		(Unknown)	Wk, Rare	——	——	——	——	——	——
808		(Unknown)	Wk, Rare	——	——	——	Wk, Rare	Wk	——
883 +884	1.40 eV	Nickel	——	——	Wk, Rare	——	Wk to Mod, Rare	——	Wk, Rare

[a] *Reference: Zaitsev (2001).*
[b] —— = *not present.*
[c] *Intensity: Wk = weak, Mod = moderate, and St = strong, based on a subjective judgment of peak height.*
[d] *Abundance: Rare = present in less than one-third of samples investigated, Common = present in more than one-third of samples investigated, and Not observed = not observed due to laser-induced fluorescence of the sample.*

Figure 3. Among the "yellow" synthetic diamonds examined during this study are those that would be described as orange-yellow, orangy yellow, and yellow (on the left, from left to right: 0.35–0.62 ct); brownish orangy yellow and orangy yellow (center: 0.28 and 0.21 ct); and yellow-brown (right: 0.22 ct). Photos by Maha Tannous.

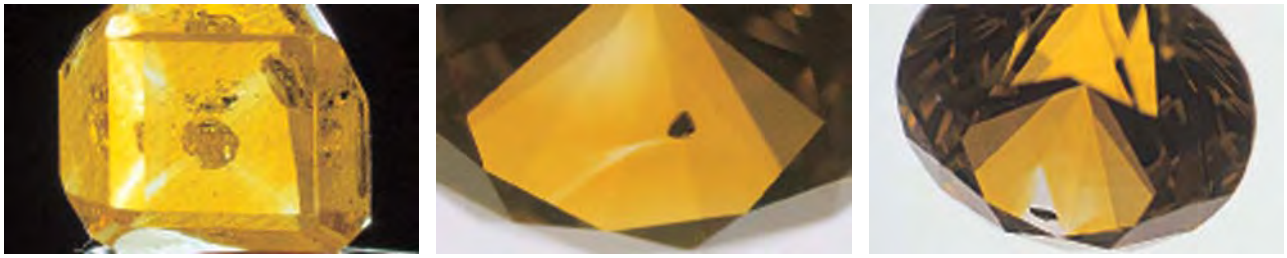


Figure 4. All the synthetic diamonds showed color zoning related to growth sectors. The yellow crystal (0.63 ct) on the far left exhibits a cross-shaped pattern of four narrow colorless zones that point toward the cube faces at the corners of the crystal; the gray area near the middle represents the seed location on which the original crystal grew. The 0.47 ct orangy yellow sample in the center has a prominent metallic inclusion, as well as color zoning due to the uneven distribution of nitrogen between growth sectors. Yellow sectors contain nitrogen, while colorless sectors contain little if any of this impurity element. The 0.57 ct sample on the far right displays similar yellow and colorless growth sectors, which are diagnostic of many laboratory-grown diamonds. Photomicrographs by J. E. Shigley; magnified 15×, 20×, and 20×.

(see, e.g., figure 7). In samples with better clarity, the relative absence of metallic inclusions could make these synthetic diamonds more difficult for gemologists to identify.

Luminescence. All the yellow samples were inert to long-wave UV radiation. When exposed to short-wave UV, one was inert, and the others fluoresced yellow-green, green, or green-yellow (one strong, 9 moderate, and 27 weak). The majority (34 samples) displayed an uneven fluorescence pattern, normally with a distinctive area that did not fluoresce. The generally weak intensity of the short-wave UV fluorescence means that observation must be carried out in a darkened room after letting one's eyes adjust to the low light level.

The one yellow-brown sample also was a type Ib diamond, but it had different UV fluorescence reactions: weak red to long-wave UV, and moderate orangy red to short-wave UV (and displaying a cuboctahedral pattern). These reactions corresponded more closely to the UV fluorescence of the pink synthetic diamonds examined in this study (see below).

Figure 8 shows the green, cross-shaped cathodoluminescence pattern of one of the yellow samples, which is diagnostic of synthetic diamonds (see, e.g., Shigley et al., 1995).

Figure 5. Immersion in water reveals the different color zoning patterns in these two yellow synthetic diamonds (0.60 and 0.49 ct; viewed table-down). These patterns depend on several factors: the shape and relative sizes of the faces on the original crystal, the area of the original crystal contained within the faceted sample, the orientation of the crystal relative to the facet arrangement, and the relative distribution of nitrogen between growth sectors. Photomicrograph by J. E. Shigley.

Figure 6. Intersecting internal graining, often in hourglass- or funnel-shaped patterns, represents another diagnostic visual feature of synthetic diamonds. These patterns are best observed through the pavilion facets (as shown here), or by looking near the edges of the table facet. Photomicrograph by J. E. Shigley; magnified 20×.

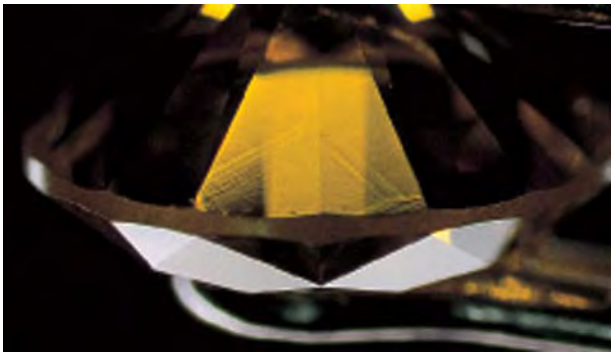


Figure 7. Metallic inclusions are another key identifying feature of laboratory-grown diamonds. They appear black and opaque in transmitted light, and gray and metallic in reflected light. They can display a wide variety of shapes, as shown in this 0.62 ct sample. Photomicrograph by J. E. Shigley; magnified 40×.

Visible Spectra. Using a prism spectroscope and transmitted light, we observed sharp absorption bands in only two of the 39 samples. The green-yellow sample (figure 9) exhibited a weak 595 nm band. The yellow-brown sample (again, see figure 3) exhibited a band at 637 nm that is caused by the NV^- (nitrogen vacancy) center (Zaitsev, 2001). The remaining 37 yellow samples displayed a gradually increasing absorption toward the ultraviolet end of the spectrum (beginning below 500 nm) that is typical for type Ib diamonds, natural and synthetic, and is the cause of their yellow color.

Advanced Instrumentation. Figure 10 presents visible-range absorption spectra for some representative samples of the synthetic diamonds examined in this study (again, see table 1). Figure 10A, for a brownish orangy yellow sample, shows sharp but very weak bands at 494, 637, and 658 nm (the weakness of these features meant that they could not be seen with the desk-model spectroscope), as well as the broad region of absorption below 500 nm that is responsible for the yellow color.

Figure 10B shows the visible-range spectrum of the one yellow-brown sample. Besides the absorption below 500 nm, there is a region of absorption from 500 to about 620 nm, as well as weak bands at 595, 658, and 741 nm and a strong band at 637 nm. These sharp bands are evidence that this type Ib synthetic diamond had been irradiated and then heated (Zaitsev, 2001). (Similar features were present in the spectrum of the green-yellow sample, but it appears that this sample was annealed at lower temperatures and/or for shorter periods of time.)

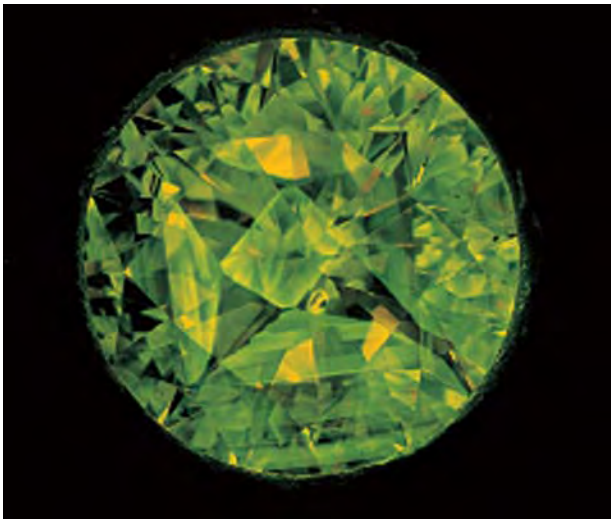


Figure 8. When exposed to a beam of electrons in a vacuum chamber, most synthetic diamonds exhibit cathodoluminescence in various colors. This luminescence often reveals the internal growth sector arrangement, such as the cross-shaped pattern seen in this 0.47 ct orangy yellow laboratory-grown diamond. These CL images are similar to those produced by the De Beers DiamondView and can be used to separate natural from synthetic diamonds (Welbourn et al., 1996). Photo by S. Muhlmeister and C. M. Breeding.

Figure 11 provides mid-infrared spectra for a range of the samples that were examined in this study. Figure 11A, which is for the same sample as in figure 10A, reveals the features below 1400 cm^{-1}

Figure 9. When examined with a prism spectroscope, the spectrum of this 0.34 ct green-yellow synthetic diamond (with a large metallic inclusion near the culet) exhibited a weak 595 nm absorption band, which indicated that it had been irradiated and heated to change its color. Photo by Maha Tannous.

that are characteristic of type Ib diamonds with a moderate amount of nitrogen.

Representative photoluminescence spectra for the samples in this study are given in figure 12. Figure 12A shows a PL spectrum for this same brownish orangy yellow sample, which is typical for the other yellow synthetic diamonds tested (again, see table 2). Figure 12B shows the PL spectrum of the same yellow-brown sample as in figure 10B.

Chemical analysis of a yellow crystal revealed the presence of Fe and Ni, which are undoubtedly from the flux metals used for diamond crystallization. The other yellow sample (which is equivalent to VS_2 clarity) did not show any trace-element impurities with EDXRF spectroscopy.

Blue. *Visual Appearance.* The 29 samples in this group were blue (18), grayish blue (6), grayish greenish blue (3), greenish blue (1), and green-blue (1). The one crystal had a greenish blue color that was different from the other samples in this group. The 28 faceted samples had colors that would be described as Fancy (6 samples), Fancy Intense (6), Fancy Deep (14), or Fancy Dark (2); two of these are shown in figure 13. In general, these faceted samples (0.13–0.50 ct) weighed less than the yellow synthetic diamonds.

The 29 laboratory-grown diamonds in this color category fell into two main groups—those that were type IIb+IIa (12 of the 24 samples for which infrared spectra were recorded), and those that also contained some isolated nitrogen in addition to boron and thus were a mixture of type IIb and Ib (11 of the 24 samples). The former contained growth sectors that were

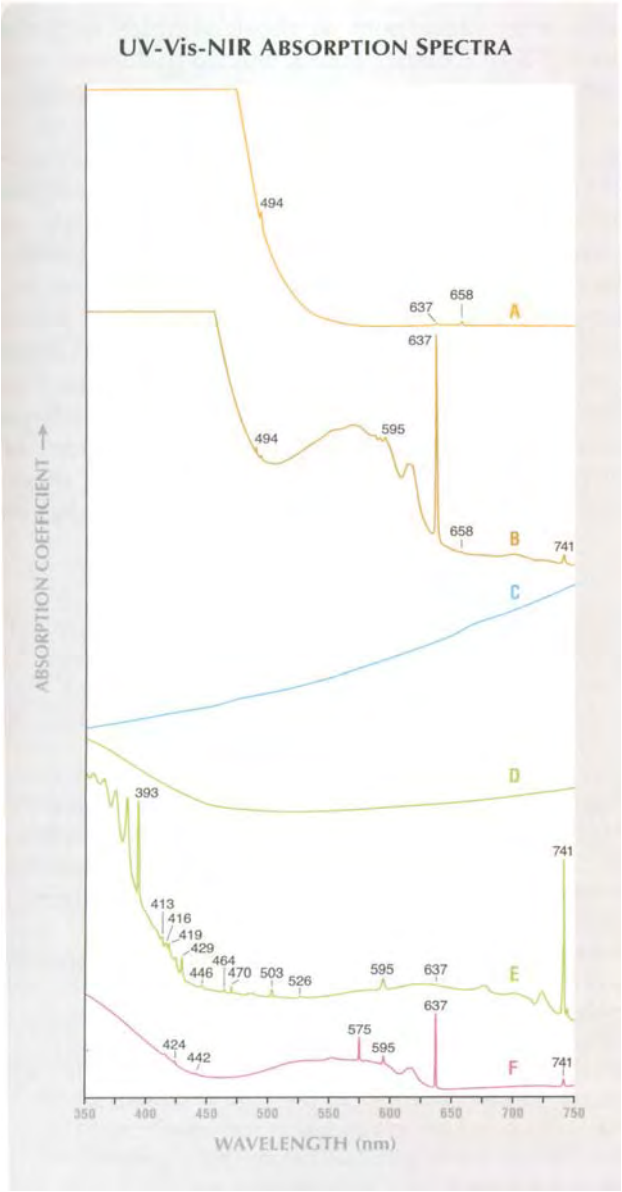


Figure 10. The visible absorption spectra of representative samples of the colored synthetic diamonds examined during this study provide information on their causes of color and, in some instances, evidence of post-growth treatments (again, see table 1). Each spectrum has been equally scaled along the horizontal and vertical axes. (A) The brownish orangy yellow color of this 0.28 ct faceted sample results from the broad region of absorption beginning below about 500 nm. Superimposed on this are weak sharp bands at 494, 637, and 658 nm. The 494 and 658 nm bands are due to the presence of Ni impurities, and the 637 nm band is due to the NV^- (nitrogen-vacancy) optical center. (B) The spectrum of the 0.22 ct faceted yellow-brown sample provides evidence that it was treated by irradiation and heating (i.e., a strong 637 nm peak, absorption between 500 and 620 nm, and weaker features at 595 and 741 nm). The 494 and 658 nm bands are again due to the presence of Ni impurities. (C) Gradually increasing absorption toward the IR region is responsible for the color of the blue synthetic diamonds, as shown for a 0.29 ct faceted sample. (D) Increasing absorption toward both the UV and IR regions, and weaker absorption between 500 and 600 nm, produces the yellowish green color of this 0.16 ct faceted sample. (E) In contrast to spectrum D, this spectrum for a 0.34 ct faceted yellowish green synthetic diamond exhibits numerous strong (393 and 741 nm) and weak absorption bands that are attributed to irradiation. (F) This 1.08 ct purplish pink crystal also reveals a number of absorption features (mainly at 575, 595, 637, and 741 nm) that provide evidence of irradiation and heat treatment.

blue and colorless, while the latter had sectors that were blue and yellow. Such blue-yellow mixed-type synthetic diamonds have been described before (Shigley et al., 1992; Rooney et al., 1993; Hainschwang and Katrusha, 2003). Figure 14 illustrates how these mixed type IIb+Ib synthetic diamonds can exhibit both blue and yellow colors when viewed face up (they also may display either a grayish or greenish overall appearance depending on the amount of nitrogen impurity present). The one treated greenish blue sample was type Ib with so little nitrogen that it could almost be considered a type IIa diamond (or a nominal type IIa; see figure 15).

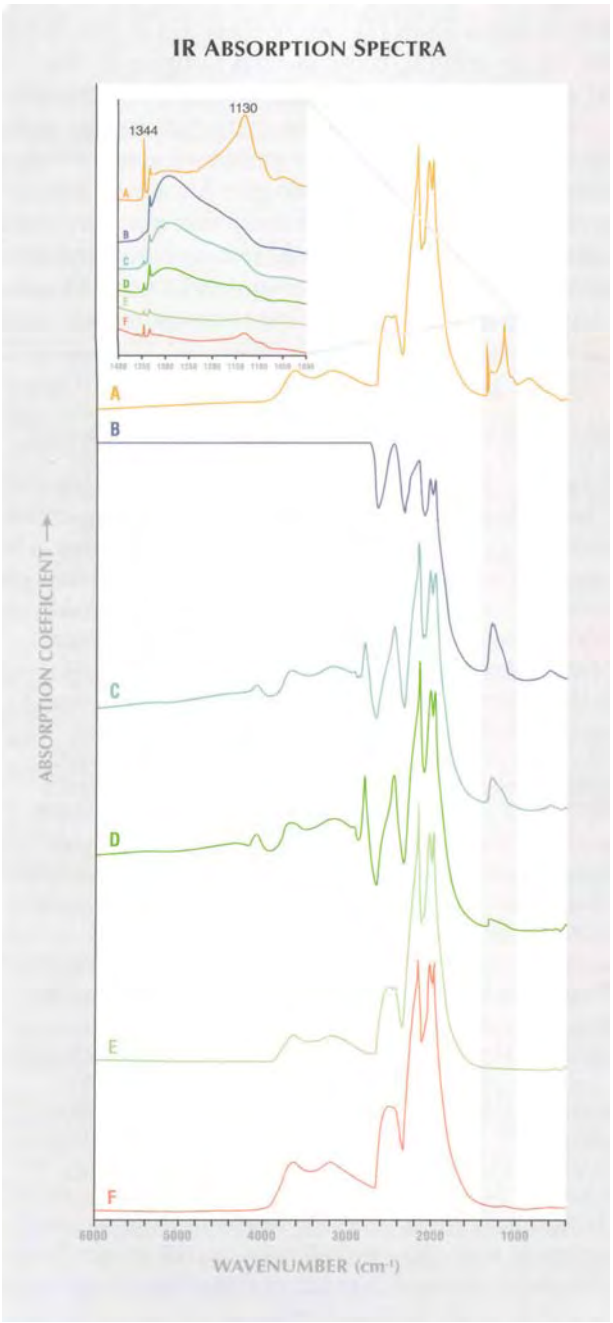


Figure 11. These mid-infrared spectra are representative of the synthetic diamond samples examined. Each spectrum has been equally scaled along the horizontal and vertical axes. For comparison, the so-called "nitrogen region" (1400–1000 cm^{-1}) of each spectrum has been expanded vertically to show weak absorption features. (A) This type Ib, 0.28 ct, faceted brownish orangy yellow sample contains a moderate amount of nitrogen impurities. (B) The type IIb blue synthetic diamonds have a small amount of type Ib nitrogen, as evidenced by the absorption at 1344 cm^{-1} in the inset for this 0.27 ct faceted example. Below 3000 cm^{-1}, the absorption exceeds the scale of the graph. (C) This 0.17 ct faceted greenish blue sample is a mixture of type IIb plus type Ib. (D) This 0.16 ct faceted green sample is also a mixture of type IIb plus a small contribution of Ib. (E) The type Ib features (see inset spectrum) in this 0.34 ct faceted green synthetic diamond are so weak that it is nearly type IIa. (F) This type Ib, 0.37 ct, faceted orangy pink sample would also be considered as nominally type IIa.

Features Seen with Magnification. All 28 faceted samples displayed some form of blue-colorless or blue-yellow color zoning (figures 16 and 17), with varying degrees of visibility, due to differences in boron (or boron and nitrogen) content between growth sectors. Only the greenish blue crystal did not show color zoning.

The clarity of these faceted samples corresponded to grades ranging from VVS to I (VVS—4 samples, VS—3, SI—9, and I—12). One or more metallic inclusions were prominent in those samples with the lower (VS to I) clarity grades, but no inclusions were readily visible in those with the better (VVS) grades.

Luminescence. When exposed to long-wave UV radiation, 17 of the faceted samples were inert, and the remainder fluoresced a very weak or weak orange or orangy red. With short-wave UV radiation, they fluoresced in various colors—11 were green, 13 were yellow-green to green-yellow, three were orangy yellow or yellowish orange, and one was orangy red. Most samples fluoresced stronger to short-wave than long-wave UV radiation. The greenish blue crystal was inert to both wavelengths. Those that fluoresced did so with weak to moderate intensities, and the majority showed cross, square, or line patterns. Except for

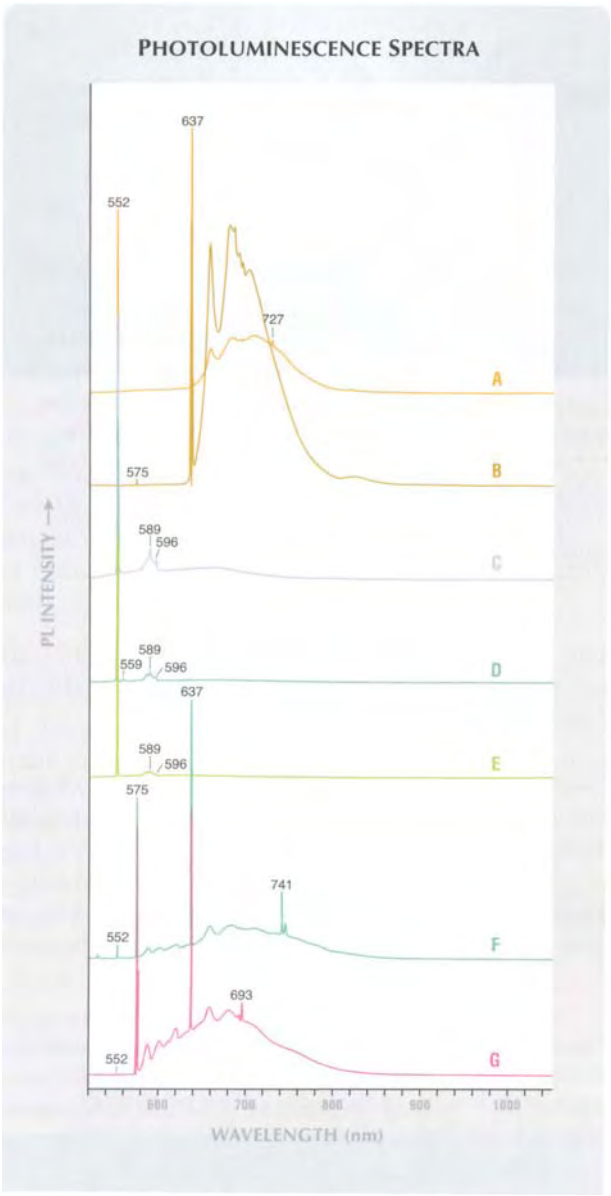


Figure 12. Important information was also derived from the photoluminescence spectra of the synthetic diamonds examined during this study (again, see table 2), as illustrated for these representative samples. (A) This brownish orangy yellow sample has features due to the NV^- center (637 nm) and nickel impurities (727 nm). (B) This irradiated and heated yellow-brown sample shows features due to the NV^0 (575 nm) and NV^- centers (637 nm). (C) The features at 552, 589, and 596 nm in this grayish blue sample are intrinsic to diamond. (D) This grayish greenish blue sample exhibits the same features as in C, along with a weak feature at 559 nm of uncertain origin. (E). The spectrum of this yellowish green sample is similar to C. (F) The 575, 637, and 741 nm bands are evidence of irradiation and heating of this bluish green sample. (G) This pink sample displays the "treatment" bands at 575 and 637 nm, as well as the 693 band due to nickel impurities.

the one sample that fluoresced orangy red, the remainder emitted greenish or yellowish phosphorescence that persisted for 60 seconds or more.

Figure 18 shows the blue cathodoluminescence with the cuboctahedral pattern typical of synthetic diamonds that was seen in the sample tested.

Visible Spectra. None of the 29 samples displayed any sharp absorption bands when viewed with the prism spectroscope.

Electrical Conductivity. All 27 of the faceted samples tested with a gemological conductometer displayed weak electrical conductivity. Each of these 27 samples also displayed visible electroluminescence (in the form of momentary flashes of white or bluish white light; i.e., "sparks") when touched by the conductometer probe. Visible electroluminescence may be seen in both natural and synthetic blue diamonds, but is more common in the synthetics because they usually contain significantly more boron.

Advanced Instrumentation. The visible absorption spectrum for a type IIb (plus weak Ib) sample, as illustrated in figure 10C, shows increasing absorption toward the red end of the spectrum. The mid-infrared spectra for two samples—the first with a higher boron content than the second—can be seen in spectra B and C of figure 11.

Photoluminescence spectra C (a grayish blue

Figure 13. Different boron contents are responsible for the variation in color saturation in the blue lab-grown diamonds (here, 0.22 and 0.27 ct). Photo by Maha Tannous.

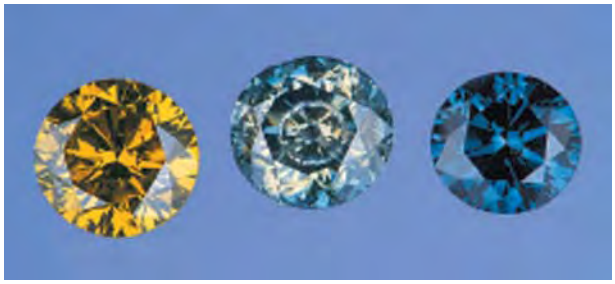


Figure 14. The 0.35 ct yellow synthetic diamond (left) is type Ib, and the 0.27 ct blue sample (right) is type IIb. The 0.36 ct sample in the center represents a mixed type Ib + IIb. Yellow and blue can clearly be seen in the face-up orientation—this combination of growth sectors can give rise to a faceted sample that would be described as green or grayish green. Photo by Maha Tannous.

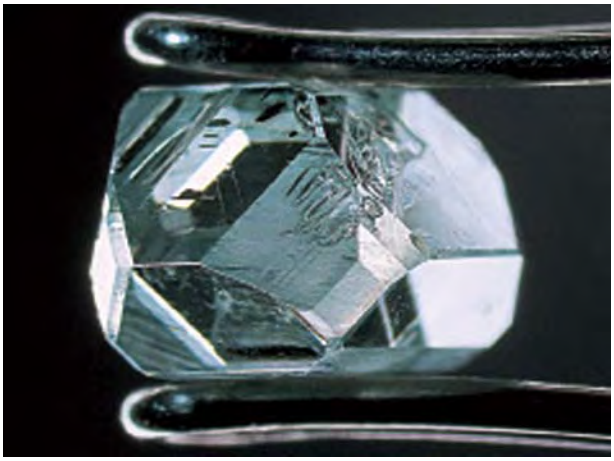


Figure 15. This 0.99 ct type Ib (nominal IIa) boron-free crystal exhibited a greenish blue color (due to radiation exposure) that was different from the blues of the other lab-grown diamonds examined during this study, which owe their coloration to the presence of boron. Photomicrograph by J. E. Shigley.

sample) and D (grayish greenish blue) of figure 12 both display bands that are intrinsic to diamond (again, see table 2).

EDXRF analysis of three samples revealed the presence of Fe and Co, or just Fe, from the metallic flux used for growth. Nickel was not detected by this method despite the presence of PL spectral bands attributed to this impurity.

Green. *Visual Appearance.* This category of 16 synthetic diamonds can also be divided into two groups. The first is a mixed type IIb+Ib (8 out of the 14 samples for which IR spectra were recorded) that, in many ways, is similar to the blue-yellow samples described above. Here, however, the green overall color due to the blue and yellow growth sectors is more apparent, so that the samples would be described as being predominantly green in the GIA color grading system.

The second group is represented by very weak type Ib (or nominal type IIa) lab-grown diamonds (6 out of the 14 samples) that owe their green color to treatment by irradiation. The two groups have different gemological properties.

Although there were only 16 samples that were basically green, they represented a broad range of hues: blue-green (1), bluish green (1), grayish bluish green (1), green (3), grayish green (3), greenish gray (1), yellowish green (2), grayish yellow-green (1), and yellow-green (3). As indicated by their visible spectra (see below), the color in all three of the yellow-green type Ib crystals (see, e.g., figure 19) had been produced by irradiation. Thus, these samples were different from the more blue-green samples that represent as-grown mixed type IIb+Ib synthetic diamonds.

The colors of the 13 faceted samples (0.16–0.41 ct; see, e.g., figure 20) would be described as Light (1), Fancy Light (2), Fancy (9), and Fancy Dark (1).

Features Seen with Magnification. The three yellow-green crystals displayed typical cuboctahedral morphology but unusual striations (again, see figure 19). Most of the 16 samples displayed some form of color zoning (with lighter and darker, or blue and yellow, growth sectors) that could be seen

Figure 16. Like nitrogen, boron becomes concentrated in some internal sectors and not in others during crystal growth, leading to these distinctive patterns of blue and colorless zones separated by sharp boundaries. Photomicrograph by J.E. Shigley; magnified 20×.

Figure 17. When viewed table-down immersed in water, the blue and colorless (samples on the left), or blue and yellow (right), zoning in cross- or square-shaped patterns is more readily apparent in these four laboratory-grown diamonds. Photomicrographs by J. E. Shigley; magnified 20×.

even in the lighter samples. The clarity of the 13 faceted samples varied from equivalent VS to I grades (VS—4 samples, SI—4, and I—5). Most of the samples corresponding to SI and I contained metallic inclusions. As shown in figure 21, some samples also displayed remnants of the original crystal surface that were located near the girdle area; such remnants could be useful for identification purposes because they can show striations or dendritic markings not seen on natural diamond crystals.

Luminescence. The samples in this category displayed a range of UV fluorescence reactions. Most of the irradiated type Ib samples exhibited very weak to weak orange to reddish orange fluorescence of similar intensities to both long- and short-wave UV radiation. However, the three yellow-green type Ib crystals fluoresced weak green to long-wave UV but were inert to short-wave UV. None of these irradiated type Ib samples exhibited fluorescence zoning patterns, nor any phosphorescence when the UV lamp was turned off.

In contrast, for the most part the mixed type IIb+Ib samples were inert to long-wave UV radiation (one fluoresced weak orange), but showed weak to moderate yellow-green or green-yellow fluorescence to short-wave UV (one fluoresced a moderate orangy yellow). All of these samples revealed some form of fluorescence zoning pattern (in the shape of a cross, square, or lines), and all displayed persistent yellow, yellow-green, or orange-yellow phosphorescence (60 seconds or more).

Figure 22 shows the blue cathodoluminescence—and the characteristic cuboctahedral pattern—of the green sample tested.

Electrical Conductivity. Six of the eight mixed-type IIb+Ib samples displayed weak electrical conductivity and visible electroluminescence. The other two were not conductive.

Figure 18. The cathodoluminescence of this 0.27 ct blue synthetic diamond reveals the distinctive arrangement of internal growth sectors. Photo by S. Muhlmeister and C. M. Breeding.

Figure 19. As determined by spectroscopy, the color of this 1.06 ct yellow-green crystal is due to irradiation and heat treatment. Also notable are the unusual curved striations that cover much of the surface. Photomicrograph by J. E. Shigley.

Figure 20. In comparison to the blue and yellow synthetic diamonds examined during this study, most of the green samples exhibited less saturated colors. Photo by Maha Tannous.

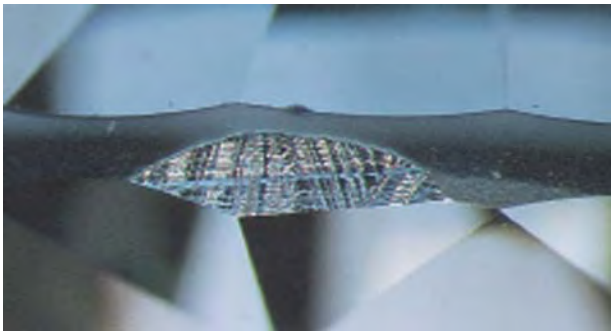


Figure 21. On occasion, small areas of the original crystal surface are retained on a faceted synthetic diamond. This 0.19 ct sample shows the striated crystal surface, which is distinctive of many laboratory-grown diamonds. Photomicrograph by J. E. Shigley; magnified 30×.

Visible Spectra. Of the 16 samples, only 4 (all yellowish green and yellow-green type Ib samples that had been irradiated) displayed sharp absorption bands in their spectra when viewed with the prism spectroscope. One displayed a sharp 595 nm band, and the three crystals each displayed a 494 nm band (again, see table 1).

Advanced Instrumentation. The visible absorption spectrum of a representative as-grown type IIb+Ib yellowish green sample (figure 10D) shows absorption toward both ends. In contrast, the spectrum of the irradiated type Ib yellowish green sample (figure 10E) is typical of that seen for an irradiated green diamond, with numerous sharp radiation-produced absorption bands (again, see table 1).

The mid-infrared spectrum of a mixed type IIb+Ib sample shows features due to both nitrogen and boron impurities (figure 11D). Figure 11E presents a similar spectrum for one of the irradiated, very weak type Ib samples, where there is an almost complete absence of nitrogen-related absorption features in the region below 1400 cm^{-1}. Thus, although the latter are type Ib synthetic diamonds, they are described as being "nominally type IIa" since their nitrogen content is so low.

The PL spectrum of the mixed type IIb + Ib diamond is dominated by intrinsic features (figure 12E), whereas that of the irradiated specimen displays several emission lines (figure 12F).

EDXRF analysis indicated the presence of Fe and Co in two of the samples tested (plus Mn, Ni, and

Figure 22. The cathodoluminescence of this 0.31 ct grayish green sample displays the distinctive arrangement of internal growth sectors identifying it as a lab-grown diamond. Photo by S. Muhlmeister and C. M. Breeding.

Figure 23. Among the "pink" samples examined during this study were those with orangy pink (0.18 ct), pink (0.21 ct), and pinkish purple (0.23 ct) hues. This is very similar to the range of hues encountered in natural pink diamonds. Photo by Maha Tannous.

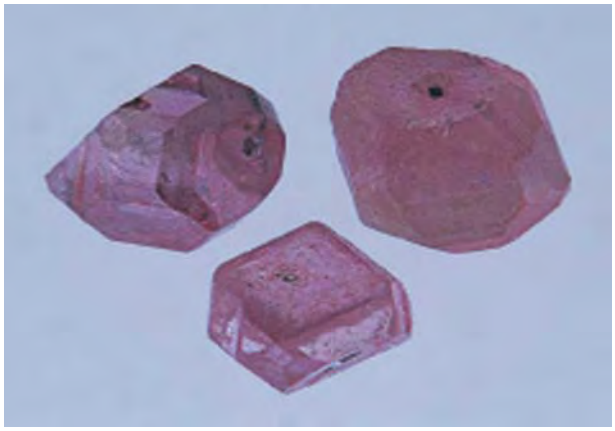


Figure 24. Note the cuboctahedral morphology of these representative samples of pink synthetic diamond crystals (0.44–0.87 ct). Photo by Maha Tannous.

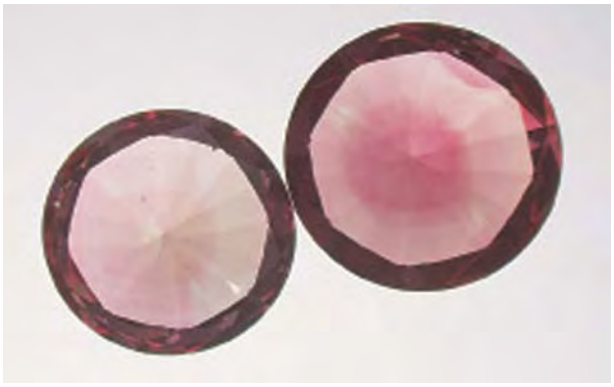


Figure 25. This comparison of color zoning patterns in a 0.32 ct sample (left) and a 0.39 sample (right) illustrates how the pattern is less visible in samples with lower saturation (as on the left). Photomicrograph by J. E. Shigley; magnified 20×, water immersion.

Cu in one of these), but no metallic impurities were detected in the third sample.

Pink. *Visual Appearance.* As with the green synthetic diamonds mentioned above, the 45 pink samples represent very low-nitrogen type Ib material (nominally type IIa due to the very weak nitrogen-related absorption bands in the infrared spectra). When grown, type Ib synthetic diamonds are yellow; the pink color of these samples is due to post-growth irradiation and heat treatment (the same process used to produce treated pink natural diamonds—Collins, 1982; Kammerling et al., 1995). These pink samples are similar in many respects to the treated red synthetic diamonds described by Moses et al. (1993).

A range of hues were represented in this group (see, e.g., figure 23): orangy pink (16), brownish orangy pink (1), pink (15), purplish pink (12), and pinkish purple (1). The color grades of the 37 faceted samples would be described as Fancy (11 samples), Fancy Intense (18), Fancy Vivid (7), and Fancy Deep (1).

Features Seen with Magnification. The eight pink crystals we examined had a typical cuboctahedral morphology (figure 24). They were on average smaller than the yellow synthetic diamond crystals we examined (0.44–1.08, versus 0.63–1.74 ct), and their shape and surface features appeared more irregular.

The clarity of the 37 faceted samples (0.16–0.51 ct) varied from VVS to I on the GIA clarity-grading system (VVS—1 sample, VS—12, SI—7, and I—17). Again, these grades were based mainly on the position and visibility of metallic inclusions. All exhibited some pattern of color zoning related to their crystal shape, although this pattern was difficult to see in those samples that were less saturated (figure 25). This zoning consisted of purplish pink and orangy pink areas separated by sharp planar graining (figure 26). Metallic inclusions were present in almost all samples (figure 27).

Luminescence. All samples in this group exhibited moderate to strong orange or orangy red long-wave

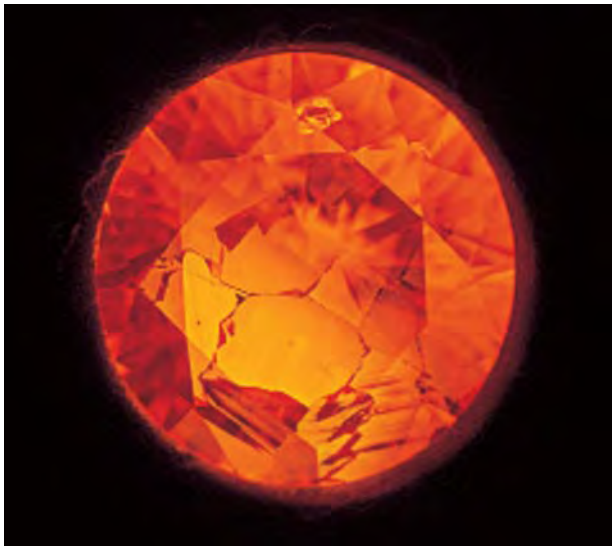
Figure 26. Shown here are two examples of color zoning seen in the pink synthetic diamonds (0.41 and 0.33 ct). The zoning appears as orangy pink and purplish pink areas separated by sharp boundaries (known as planar graining) that are often perpendicular to the table (left), but may occur at an angle to this facet (right). This color zoning is best seen by observing close to the girdle plane of the sample. Photomicrographs by J. E. Shigley.

Figure 27. The metallic inclusion in this 0.41 ct sample displays a brownish halo as the result of a tension fracture being created when the inclusion solidified. Photomicrograph by J. E. Shigley; magnified 40×.

UV fluorescence. When exposed to short-wave UV radiation, the samples fluoresced weak, moderate, or strong orange. Twenty-eight of the 45 samples had stronger long-wave than short-wave UV fluorescence, while the remainder appeared to fluoresce in similar intensities to both wavelengths. In most cases, these fluorescence reactions appeared to be evenly distributed, although cross-like or line patterns could be seen in a few. When the UV lamp was turned off, 7 of the 45 samples displayed a weak orange phosphorescence of limited duration (5–10 seconds); the remaining samples did not phosphoresce.

Figure 28 shows the orange cathodoluminescence pattern of the one pink sample tested.

Figure 28. The cathodoluminescence of this 0.39 ct pink synthetic diamond reveals the growth-sector arrangement typically seen in synthetic diamonds. Photo by S. Muhlmeister and C. M. Breeding.



Visible Spectra. When observed with the prism spectroscope, all but 2 of the 45 samples showed a sharp absorption line at 637 nm, and 19 displayed sharp bands at 595 nm.

Advanced Instrumentation. These pink synthetic diamonds displayed a number of sharp absorption bands in their visible spectra (see table 1 and figure 10F). These spectral features are very characteristic of yellow type Ib diamonds that have been irradiated and heated to create a pink-to-red color (Collins, 1982). The infrared spectra of this group (figure 11F) indicate that these samples contain little nitrogen, as evidenced by the very weak nitrogen-related absorption features below 1400 cm^{-1}. The PL spectrum in figure 12G shows several of the same features as the visible spectra, along with a peak at 693 nm due to nickel impurities.

When analyzed by EDXRF, Fe, Ni, and Co (and possibly Cu) were detected in three of four samples (no metals were detected in the fourth sample analyzed).

DISCUSSION AND IDENTIFICATION

As we have seen from the data presented above (and summarized in the *G&G* Data Depository at www.gia.edu/gemsandgemology), many of the characteristics of the new synthetic diamonds supplied by Chatham's Asian manufacturer do not differ appreciably from others that have been grown by this method (HPHT). Nevertheless, as is often the case with synthetic materials that are produced by different manufacturers, there are features present in some of these synthetic diamonds that are unlike those we typically see in other HPHT-grown products.

One of the most interesting observations is that the majority of the irradiated pink and green synthetic diamonds contained so little nitrogen that one would expect them to be very pale in their "as grown" state, although we are aware (based on our experience with natural diamonds) that low concentrations of isolated nitrogen can result in strong colors. As stated above, many were close to being classified as type IIa. This is important because to date low-nitrogen-content synthetic diamonds have been difficult to manufacture, and the only ones we had

seen previously were those created in the manufacturer's attempt to grow near-colorless material. Unfortunately, we do not know what the original appearance of the Chatham pink and green samples was before they were irradiated. It may well be that the low nitrogen concentration is necessary to produce the lighter pink colors. More information is needed before we can assess the significance of this development.

Another interesting fact about this new product is the availability of as-grown greens, which had seldom been seen before in synthetic diamonds. The curious combination of blue type IIb and yellow type Ib in the same crystal, which produces a green face-up color in a finished stone, may be a consideration for some who prefer not to have irradiated material.

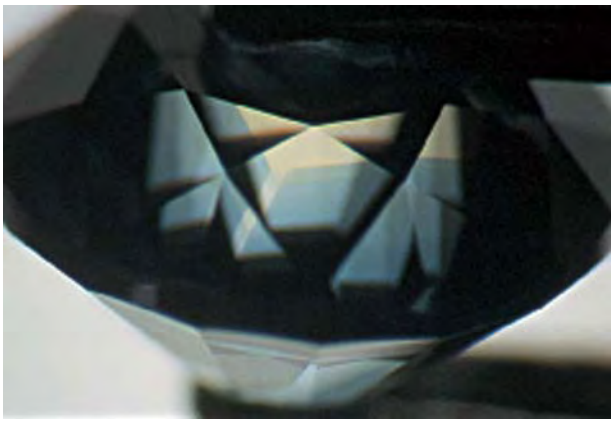
Also important, as noted above, is the fact that the colors of a great many of these synthetic diamonds more closely resemble those commonly seen in natural colored diamonds, particularly in the blues, pinks, and greens. For the most part, the colors of other synthetic diamonds have been "better than nature," as is typical of synthetic gem materials, whether they are diamonds, rubies, or emeralds. The danger here is the possibility that a gemologist might let his or her guard down when it comes to identifying one of these lab-grown diamonds by virtue of the fact that they do not "look" lab grown. While this may seem like a basic issue, it is nonetheless a very real trap that can be easy to fall into.

As for the identification of these laboratory-created diamonds, the indications and features of those we examined are fairly consistent with those produced by other HPHT manufacturers in the past. Many still contain metallic flux inclusions (which, if present in sufficient quantity, would make the host gem magnetic), still show patterned color zoning and ultraviolet fluorescence related to their cuboctahedral morphology, and still display characteristic features using advanced instrumentation, such as nickel-related absorption and photoluminescence lines and the presence of Ni, Co, or Fe in their chemistry. (The occurrence of nickel is extremely rare in natural diamonds [see Chalain, 2003].) These samples, however, showed some additional features worth noting.

The type IIb or mixed type IIb+Ib blue-to-green samples all showed the color zoning that is distinctive of synthetic diamonds (figure 29). In addition, the presence of blue and yellow color zoning in the same item does not occur in natural diamonds. These features are diagnostic and make identification of these synthetics fairly straightforward. It should be noted that, unlike other colors, the fact that the short-wave UV fluorescence is commonly stronger than the long-wave UV is not particularly useful with blues. While natural type IIb blues often do not fluoresce at all, it is common for them to show this property when they do (King et al., 1998).

There is little information published about synthetic pink diamonds, primarily because so few have been seen until now. Most irradiated type Ib synthetic diamonds we examined previously were red. Identification of the pinks should first revolve around establishing the fact that they are irradiated to this color, which is a rare occurrence even in natural diamonds. It is well documented that most natural pink diamonds owe their color to plastic deformation of their crystal lattice (see, e.g.,. Chapman and Humble, 1991; Collins, 1982, 2001), which gives rise to distinctive properties such as strong strain visible in polarized light (figure 30) and related strong graining and color zoning (figure 31). These features are not present in the pink Chatham synthetic diamonds, which should immediately alert the gemologist that a more critical examination is warranted (figure 32). Of course, as mentioned earlier, orange fluorescence to long- and short-wave ultraviolet radi-

Figure 29. All of the type IIb and mixed type IIb + Ib samples we examined for this study displayed color zoning following the cubo-octahedral habit of the crystals, which is very characteristic of synthetic diamonds. This sample shows blue and yellow color zoning following a distinctly unnatural pattern. While most of the samples in this study showed some kind of unnatural zoning, the patterns in these types were by far the most pronounced. Photomicrograph by Shane F. McClure; magnified 28×.



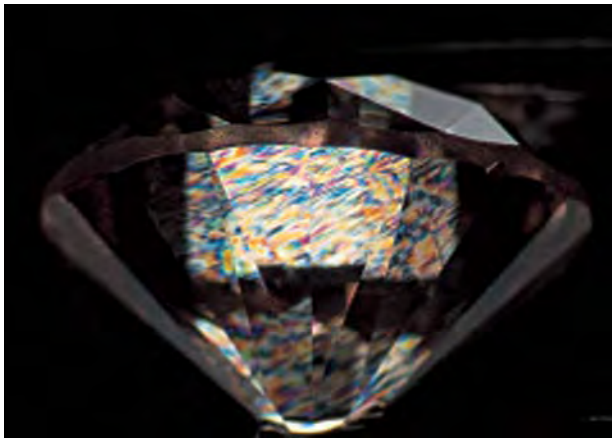


Figure 30. The strong strain usually present in natural pink diamonds (seen here in polarized light) was not observed in any of the Chatham synthetic pink diamonds examined. Photomicrograph by Shane F. McClure, magnified 16×.

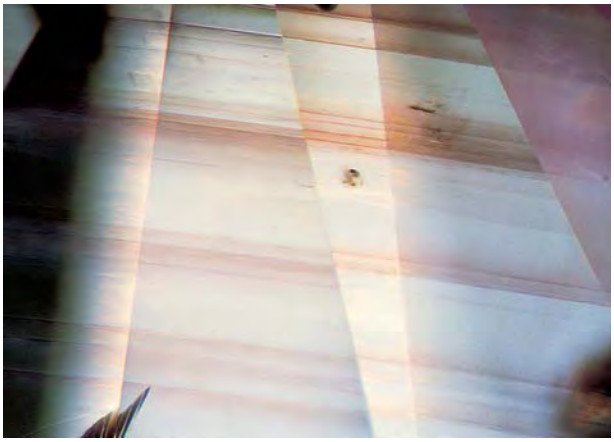


Figure 31. Color zoning in natural pink diamonds typically follows the strain patterns in the form of uneven parallel bands, as shown here, which is not seen in pink laboratory-grown diamonds. Photomicrograph by John I. Koivula; magnified 15×.

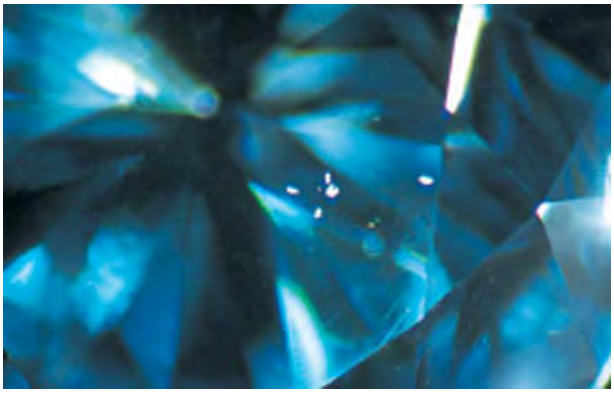
ation and the presence of 595, 637, as well as (possibly) 575 nm lines in a prism spectroscope are indications that a pink diamond is an irradiated type Ib. However, both natural and synthetic type Ib diamonds can be irradiated and heated to produce a pink color. Whether it is natural or lab grown must be determined by inclusions, color zoning, or analysis with advanced techniques. It should be noted that some rare natural type IIa pink diamonds may also fluoresce orange (Moses et al., 1993).

The most significant aspect of these new synthetics from the point of view of identification reflects a continuing trend with synthetic diamonds in general (Shigley et al., 2002). As might be expected, improvements in the growth technique have led to steady improvements in the product, so that they tend to be cleaner overall (figure 33). The fluorescence patterns are also diminishing in strength and size, such that some of the samples in this study did not fluoresce at all. This means that the gemologist must be extremely careful when examining suspect stones.

None of the samples in this study were completely free of inclusions. Even those that were of VVS quality contained flux in the form of sparse clouds (figure 34). With practice and experience, these clouds can be recognized by their appearance, but it is not an easy separation. Suffice it to say that a diamond that contains only a sparse cloud as a clarity feature should be examined carefully.

Figure 32. The color zoning seen in these pink synthetic diamonds consisted of distinct areas of purplish pink and orangy pink with sharp, well-defined borders. Photomicrograph by James Shigley; magnified 15×.

Figure 33. The size and frequency of metallic inclusions in modern synthetic diamonds has been diminishing for some time. Often they are small and difficult to recognize as metallic flux. Photomicrograph by Shane F. McClure; magnified 40×.



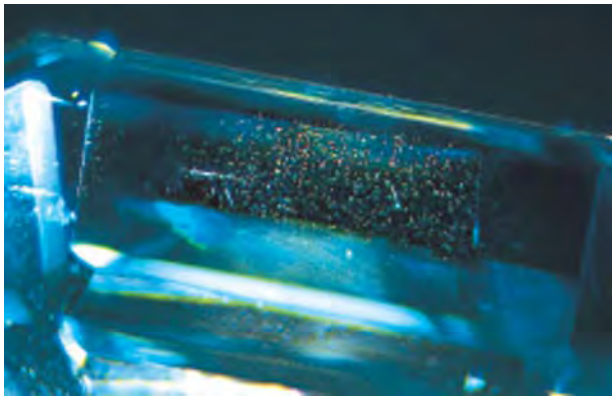


Figure 34. Sometimes the only inclusions present in these samples were sparse clouds of pinpoints. With some experience, it is possible, though difficult, to recognize the difference in appearance between these clouds and those found in natural diamonds. Photomicrograph by Shane F. McClure; magnified 37×.

It is important to point out, however, that all of the samples we tested for this report could be identified by gemological means. In some cases, careful examination is required, but the combination of inclusions, graining, fluorescence, and color zoning would conclusively identify all these samples as synthetic.

The De Beers Diamond Trading Company's DiamondView instrument is also very useful to detect characteristic surface patterns in higher-energy UV fluorescence. This instrument is now available to the trade, but it is considerably more expensive than standard gemological instruments, and training is required to interpret the results correctly.

CONCLUSIONS

A new group of laboratory-grown diamonds being marketed by Chatham Created Gems—under the name "Chatham Created Diamonds"—represents a wide range of hues and, in some cases, very natural-looking color saturations. The samples examined in this study exhibited many visual features that would aid in their identification, and testing with advanced instrumentation would provide additional spectral and chemical evidence of their laboratory origin. The increasing availability of synthetic diamonds such as the ones examined here reinforces the need for gemologists to know the means of their identification.

ABOUT THE AUTHORS

Dr. Shigley is director, and Drs. Breeding and Shen are research scientists, at GIA Research in Carlsbad. Mr. McClure is director, and Mr. Muhlmeister is a senior research associate, in the Identification Services department at the GIA Gem Laboratory, Carlsbad.

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