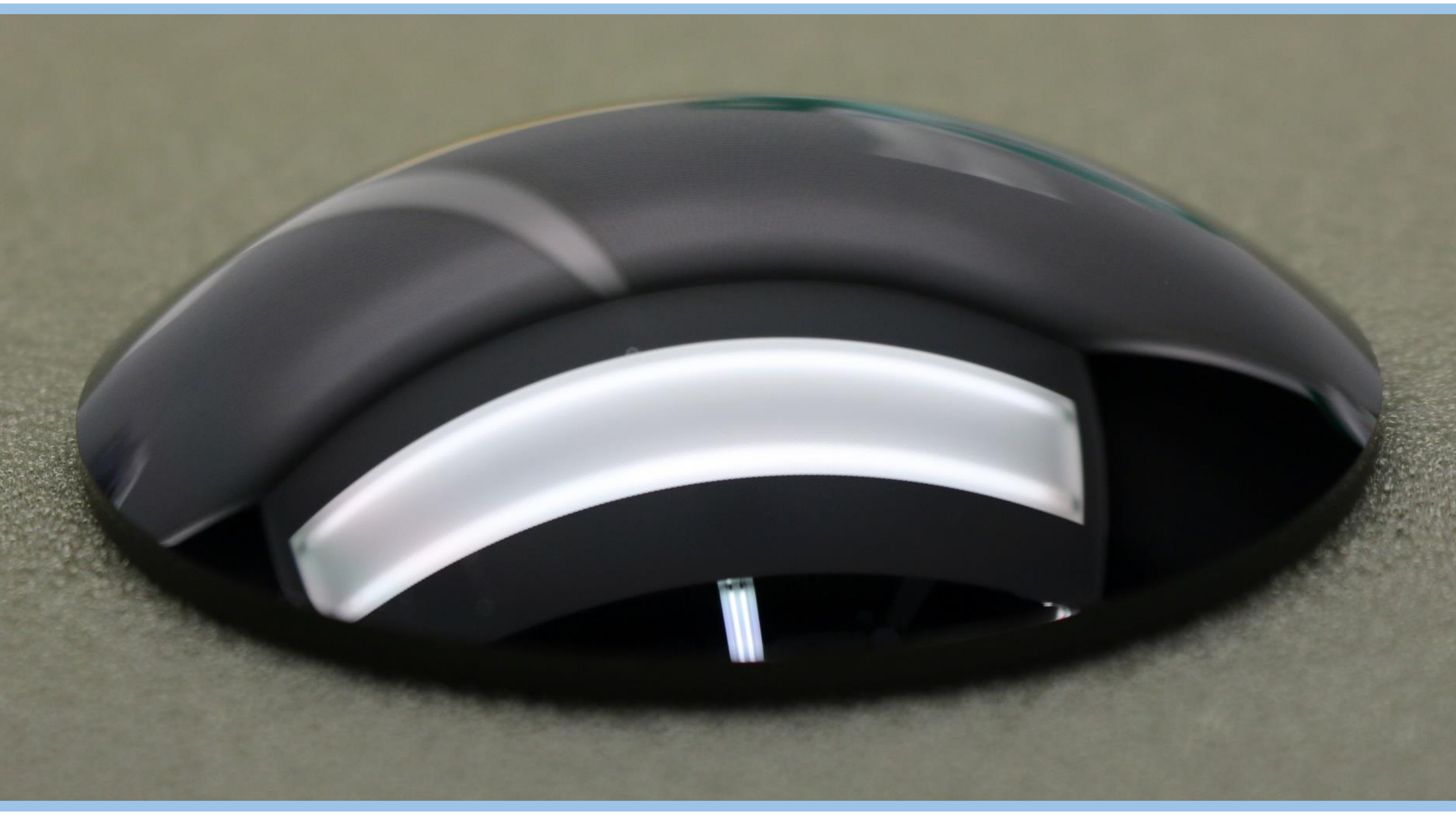

White Paper

Diamond Like Carbon

Why Intlvac's Coatings & Systems are Best Positioned to Support the Booming IR Optics Market

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BACKGROUND

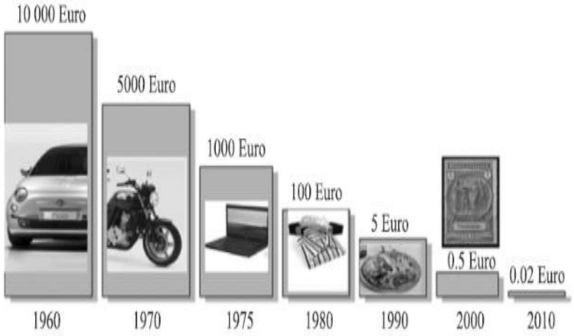

Figure 1: Cost evolution of single pixel sensors.

Figure 2: Infrared Forehead Thermometer. *ULINE.*

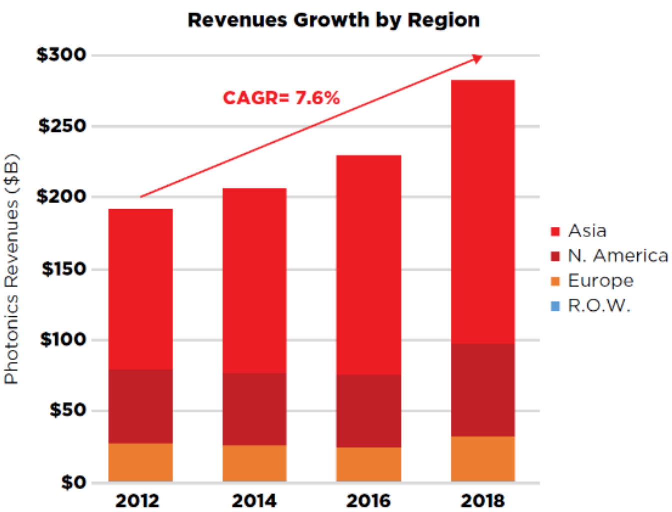

Figure 3: Photonics Industry growth.

"There's more to this than meets the eye." This must have crossed Sir Isaac Newton's mind when he noticed that white light was made up of a spectrum of different colours. Humans lack the receptors in their eyes that allow us to see longer/shorter waves of light. Though, as these physical phenomena were observed, someone might have noticed that one part of the rainbow can not only be seen, but also felt: a hint at the fringes of IR.

Once we were able to electronically image other wavelengths of the EM spectrum a whole new world was revealed to us. From the 70's onward IR optical technology evolved into more specialized roles such as thermal imaging for medical/cultural diagnostics, structure evaluation, remote sensing and more (1)

Likewise, the cost reduction of the technology, driven by its advance, now offers significant accessibility. For example, CCTV's with Night Vision capability meant for civil use are prevalent now, and can be had for $20.00 USD or less, which offer quality that was strictly military grade not so long ago (1)(2)(3).

What's more, as the COVID-19 pandemic continues, IR technology has become even more important within medical applications for things such as the aforementioned thermal applications like handheld IR thermometers (4).

The growth of the photonics industry is eclipsing $282B and is supported by a 7.6% CAGR since 2012 according to SPIE reports (5). Further, IR specifically has shown a 25% increase in CAGR between 2014-2019 according to Yole Dévelopment (6). The potential of IR is vast, which is a facet of the larger industry in which it resides. Though, there is one additional trait IR radiation holds over other types within the EM spectrum: IR radiation is emitted by all forms of matter (7). It is a universal medium for gathering common empirical data.

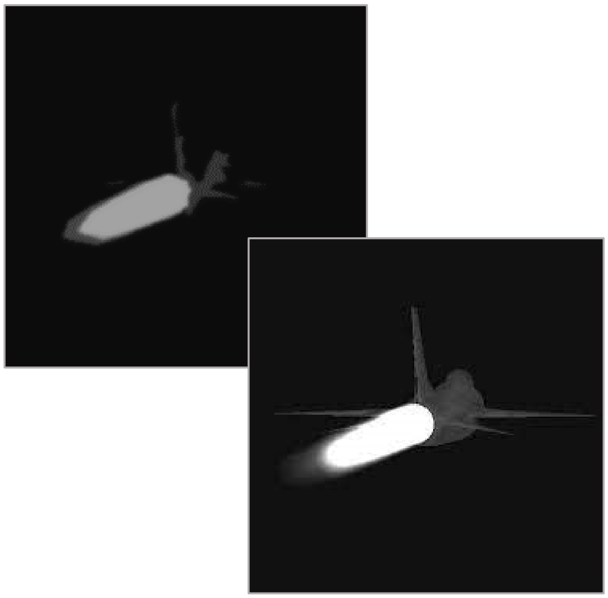

Figure 4: Example of high reflectance signal loss in IR.

However, viewing images in the IR is still a challenge since many windows we would use for visible light are opaque in the Infrared. Special materials are used for these windows, but these materials have their own challenges. Silicon and Germanium slow the speed of light down when it passes through them, and the way we define that is their Index of Refraction. Si and Ge are the most common materials for IR transmission; materials with these properties have a higher incidence of reflection for the light as it hits the surface. The amount reflected can be as high as 40%, which means those photons do not make it to the sensor. Alas, losing that much information in the Information Age is undesirable to say the least. To recover that light, thin films are applied to the surface and is where our materials science begins.

WHY IS IT CALLED DIAMOND LIKE CARBON?

The ternary phase diagram of Carbon depicts it with its other bonding states & configurations (8). Carbon shows bonding in two main configurations: sp^2 (109.5° bond angles) and sp^3 (120° bond angles). The extremes on this scale define the points where pure graphite, and pure diamond reside (8). Combinations of these two bonds in the same mass define what is called the "amorphousness" of DLC (8). This descriptor hints at how the high degree of order of the crystalline graphite/diamond has now deformed into something more atomically "spongey". Vibrations are no longer patterned, and order is short range. The variation of sp^2 – sp^3 bond ratios of carbon allows the element to offer a wide range of traits.

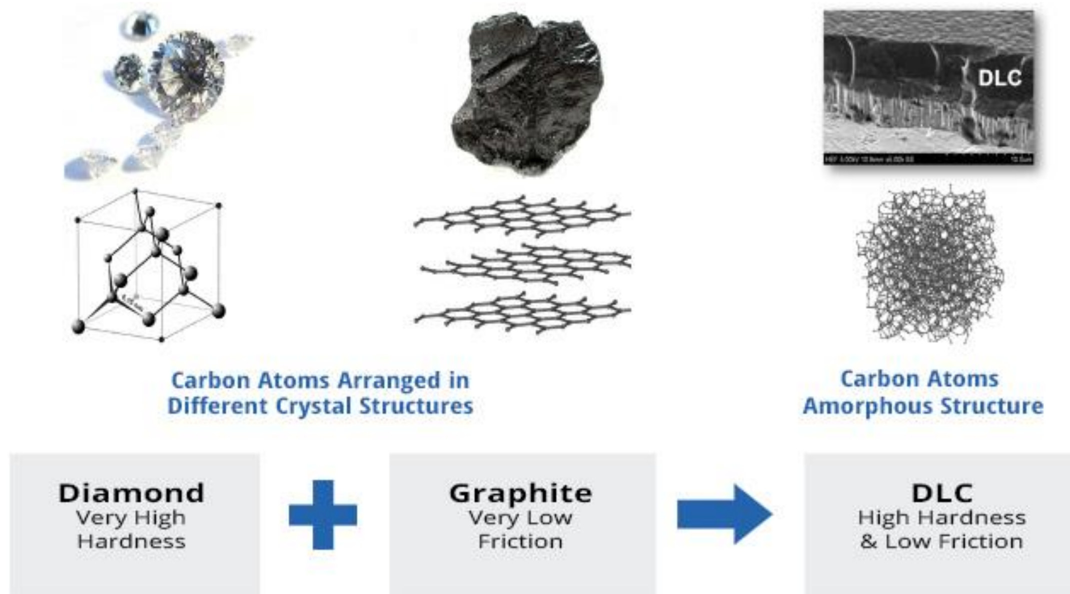

Figure 5: Diamond, Graphite, and Diamond Like Carbon traits

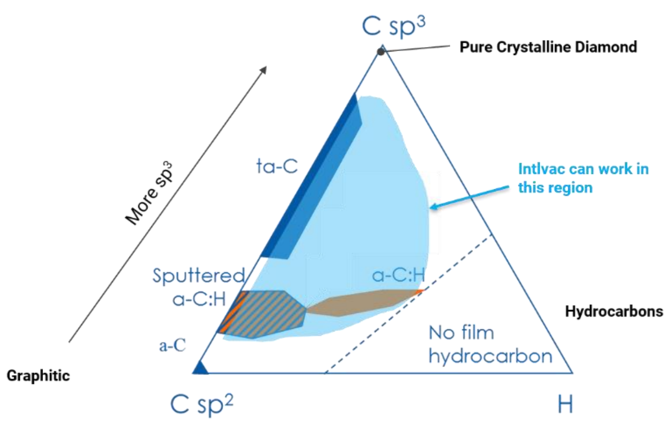

Figure 6: Phase diagram of carbon showing graphite, diamond, and hydrocarbons. Highlighted area depicts region of $sp^2 – sp^3$ selectivity for Intlvac

Graphite is a slippery material whose bonds are weak between sheets It is a material that absorbs most light. It is also electrically conductive along its layers, but not across them (9). Diamond crystals are much more tightly packed and do not exhibit the same erosion as graphite. Diamond is also an excellent reflector of light with a high refractive index (10). These are the traits that DLC and their films adopt according to the $sp^2 – sp^3$ composition.

DLC is shown to have variable electrical properties. It ranges from behaviour modelling a semimetal which defines a small overlap between the top of the valence band and the bottom of the conduction band, to a wide band gap insulator (10). Their high disorder prevents them from being suitable as a semi conductor material, however they do offer significant potential to be used for passive electrical devices (10).

The combination of its optical properties and physical properties what make it truly remarkable. Optically, DLC films are transparent in the infrared, and show a variable Index of Refraction of 1.7-2.4 depending on the deposition conditions (10).

Physically, it offers a high Young's Modulus, and hardness, which are a result of its diamond characteristic, and defines the excellent scratch

Sample	% sp3	% sp2
C7	93.01	6.99
C9	72.83	27.17
E1	16.84	83.16
E3	14.62	85.38
A9	12.75	87.25
E5	11.45	88.55
A1	11.34	88.66
A3	9.71	90.29
C1	9.04	90.96
C3	8.66	91.34
A7	8.36	91.64
C5	8.34	91.66
A5	7.65	92.35

Table 1: $sp^2 - sp^3$ percentage variability. Values can be adjusted on demand to achieve selective properties.

resistance of the material. DLCs notably maintain the low friction coefficient that graphite exhibits (10).

Recall that since Infrared radiation is a measure of heat, DLCs are excellent for applications that see wide temperature ranges.

Few other materials offer such synergy between their properties which is a key point in understanding how the materials science connects with its related advanced manufacturing and technological innovations.

For instance: sometimes, an optic may require the inclusion of a sacrificial lens to shield the main lens beneath. What if you could produce products that combine those traits into one? What could be saved in production cost, time, weight, complexity, etc.? In the world of manufacturing, one component is not simply one component; there is always more at stake.

A gradient of bond ratios is a profound advantage because it offers a unique but straightforward way to achieve highly optimized and precise traits tailored to the requirements at hand. The trick is being able to control the $sp^2 - sp^3$ bond ratio without oversaturating the compound with hydrogen; a skill that Intlvac has developed over many years. No longer is DLC a catch all term to represent the entirety of its phase diagram. Intlvac has succeeded in developing it to a level where graduated selectivity is feasible via our technical experts, optimized processes, and robust systems.

It is prudent to mention that DLC is also a biocompatible product to many living cells, and is also highly corrosion resistant (11).

Figure 7: 450mm diameter coated DLC wafer.

INTLVAC'S AEGIS DLC SYSTEM

Designed for the Future

Intlvac's Aegis DLC system employs Plasma Enhanced Chemical Vapour Deposition (PECVD) and is well positioned to lift this industry to the next level. This is because it satisfies the 3 main prerequisites of advancing a novel technology into a common commercial product. Manufacturability: how long does it take to make, what are the supply demands, are the resources readily available? Consistency: is the process easily repeatable? What kind of ramp up, cool down, and/or servicing is required? And, of course, quality: is the final result worth what it takes to achieve? These are the bottlenecks that prevent novel technologies from becoming widespread and govern things like price, accessibility, ease/rate of production, marketability, and more.

The Intlvac Aegis DLC system offers a more complete suite than what exists on the market today. The large 500mm coating area maximizes throughput and offers users a large surface to coat many parts at once or a single large 450mm diameter substrate. This throughput versatility allows users to adapt to production demands and customer needs. Many years of process development and system development in tandem have taught us some of the nuances of achieving single layer uniformity via systems that show mass production levels of consistency.

Designed for The Future pt. 2

Figure 8: President Dino Deligiannis holding newly coated 450mm diameter Silicon wafer with DLC.

DLC films can be grown using a large variety of techniques: Magnetron Sputtering, Cathodic Arc, Hot Filament, Kaufman style Ion Sources, End Hall Ions Sources, Plasma Torch, ECR Plasma, and PECVD. All techniques have their own merit for their specific applications. 1994 was considered late into the game when Intlvac began its DLC research using End Hall ion Sources. Ten years later when a new End Hall source was released to the markets, we worked on this for Infrared Optical coatings with success. It is still an option to produce the DLC by decomposing a hydrocarbon gas in the directed plasma produced by ion sources. However, we quickly discovered that PECVD had much better control of the growing DLC film, much better coverage and uniformity over larger areas, less dust, and virtually no pin hole defects due to the proprietary technology that we developed.

Intlvac's Aegis DLC system is now in its 4th generation from its inception 13 years ago, which is added on top of the 14 years of research Intlvac began its exploration with. Seeing that the industry was heading toward cheaper and more accessible IR, it was critical to design a system that was provided reliable performance meant to support mass production. The current 4th generation systems *exceeded* design expectations: one of the team mused if it could be run continuously for months.

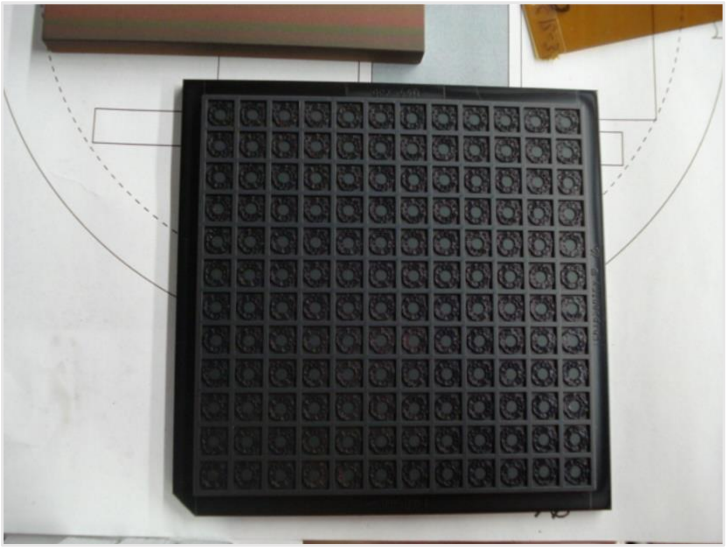

Figure 9: The ability to coat so many wafers at once at equal quality is paramount to the production potential of the Aegis DLC system.

A test was soon performed to keep the system running and producing for 8-hour shifts, 3 times per day. The testing was stopped after 7 days, but the system showed no signs of inconsistency. It remained at optimal performance the entire time.

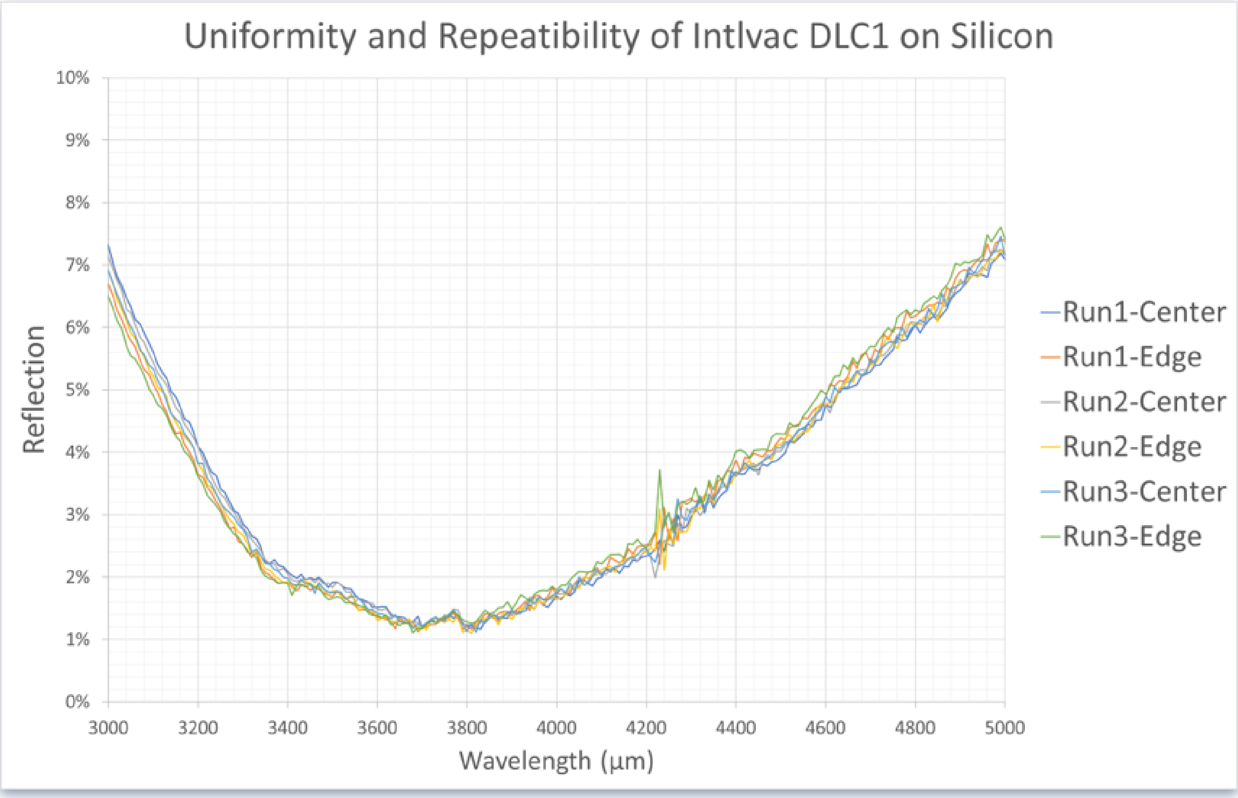

Figure 10: Graph showing uniformity and repeatability of DLC processes. Film characteristics also show remarkable performance across the entirety of the coating, a key difficulty in large area thin film coatings meant for performance.

COAT ANYTHING, EXPLORE EVERYTHING

Intlvac's Aegis DLC system is excellent at coating atop a variety of substrates. While industry staples such as Silicon and Germanium are easily coated upon, nearly the entire suite of Chalconides are available to be deposited on as well with excellent adhesion.

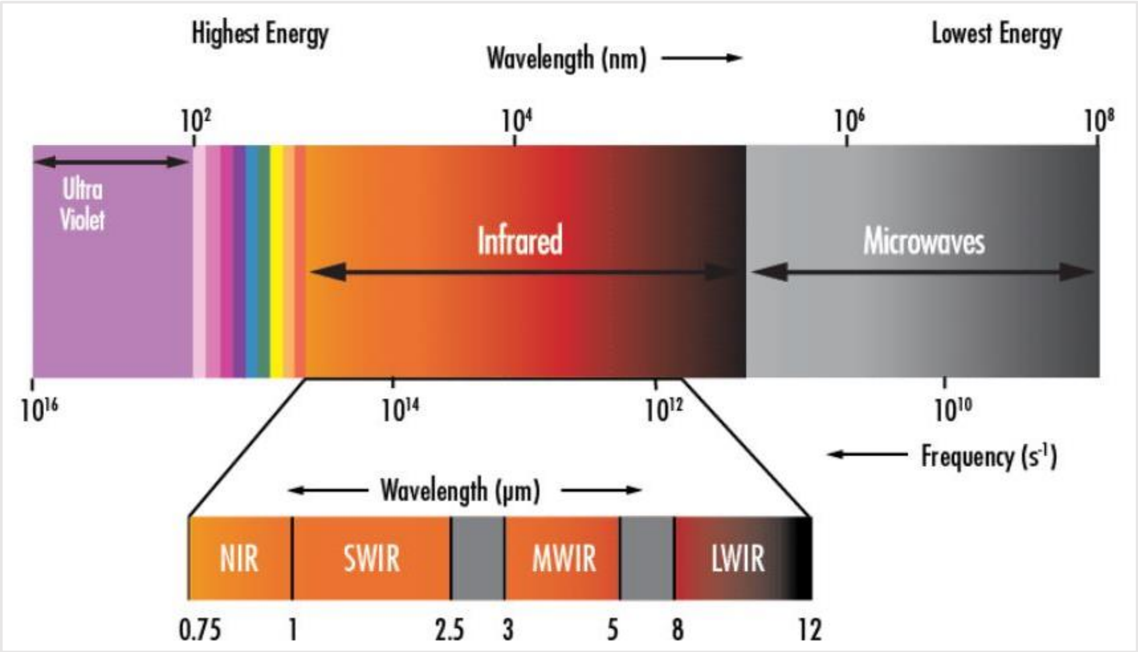

Figure 12: Electromagnetic Spectrum highlighting the IR Range. *Edmund Optics.*

The IR spectrum is vast and stretches from the edge of the visible spectrum just beyond red light around 700nm, all the way to 1mm. The production power that 4th generation DLC systems offer positions users well to explore and take advantage of new possibilities that could arise. Diamond Like Carbon can be grown from virtually many hydrocarbon sources, leaving further room for research and process development. Intlvac has explored most all the hydrocarbons, gases, and other materials to optimize our DLC. Our system is well equipped to handle each of them.

CONCLUSION

As the IR industry booms, more control, manufacturing power, and excellence is needed. Some might say that the IR spectral range is the most intriguing, and most useful; we certainly would. The IR range was traditionally explored for military applications, but it has seen a marked shift toward accessibility for the mass market. It is already well integrated via examples such as: Handheld IR

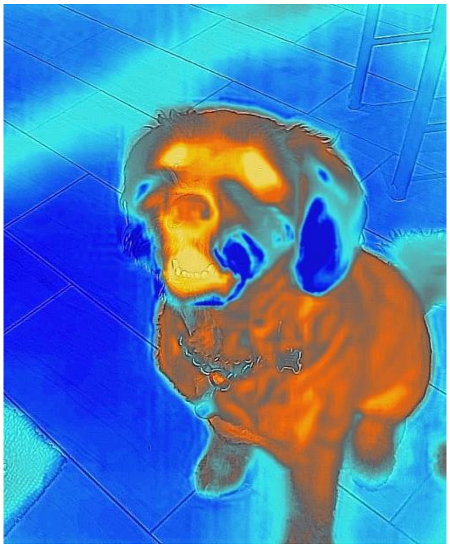

Figure 13: IR photo taken using commercial technology.

thermometers, consumer level night vision CCTV's, photography products, and more. It is a field that is experiencing significant maturation, and to see it through requires systems and techniques that can not only keep up, but act as platforms for growth. Intlvac's Aegis DLC system and coatings are each well positioned to accomplish this feat. Sensing approaching technologies is a driving force for our innovation so that the systems we develop can serve you best not only now, but tomorrow and beyond.

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ABOUT INTLVAC

At Intlvac, we challenge ourselves everyday to deliver world class coating systems, processes, and coatings through constant innovation. Our growth as a company is led by a large commitment to R&D. We have a passion for unlocking the nuances of materials science. When our customers push the limits of our products toward success, we feel that our visions have been realized.

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