OPTO-ELECTRONICS REVIEW **21**(2), 153–181

DOI: 10.2478/s11772-013-0089-3

Review of night vision technology

INVITED PAPER

K. CHRZANOWSKI*[1,2]

[1]Institute of Optoelectronics, Military University of Technology, 2 Kaliskiego Str., 00–908 Warsaw, Poland
[2]Inframet, 24 Graniczna Str., Kwirynów, 05–082 Stare Babice, Poland

Night vision based on technology of image intensifier tubes is the oldest electro-optical surveillance technology. However, it receives much less attention from international scientific community than thermal imagers or visible/NIR imagers due to series of reasons. This paper presents a review of a modern night vision technology and can help readers to understand sophisticated situation on the international night vision market.

Keywords: night vision technology, image intensifier tubes.

List of abbreviations

ANVIS – aviator night vision imaging system (a term used commonly for binocular night vision goggles),
CCD – charge couple device (a technology for constructing integrated circuits that use a movement of electrical charge by "shifting" signals between stages within the device one at a time),
CCTV – close circuit television (type of visible/NIR cameras used for short range surveillance)
CMOS – complementary metal-oxide-semiconductor (a technology that uses pairs of *p*-type and *n*-type metal oxide semiconductor field effect transistors for constructing image sensors
CRT – cathode ray tube (a vacuum tube containing an electron gun and a phosphor screen used to generate images)
EMCCD – electron multiplying charge coupled device
fc – foot candela
fL – foot lambert
ENVG – enhanced night vision goggles
EBAPS – electron bombarded active pixel sensor
FOM – figure of merit
FOV – field of view
HUD – head-up display
ICCD – intensified CCD (a technology that uses imaging modules achieved by combing image intensifier tube with CCD sensor)
IIT – image intensifier tube
lp/mm – line pair per millimeter
lp/mrad – line per miliradian
MCP – micro channel plate
MIL standard – a United States defence standard, often called a military standard
NIR – near infrared
NVD – night vision device
NVG – night vision goggles
RMS – root mean square
SNR – signal to noise ratio
SWIR – short wave infrared
TFT LCD – thin film transistor liquid crystal display.

*e-mail: kch@inframet.com

1. Introduction

Humans achieve ability to see at night conditions by using several different imaging systems: night vision devices (image intensifier systems), thermal imagers, SWIR imagers, and some more sensitive visible/NIR (CCD/CMOS/ICCD/EMCCD) cameras. However, due to historical reasons, night vision technology is usually understood as night vision devices.

Night vision devices (NVDs) are apparently simple systems built from three main blocks: optical objective, image intensifier tube, and optical ocular (Fig. 1).

The task of the optical objective is to create low intensity, invisible image of the observed scenery at input plane of the image intensifier tube. The latter tube consisting of a photocathode, an anode in form of a phosphor screen, and other components, intensifies an input low-luminance image into a brighter image created on the anode (screen). The latter image is seen by human observer using the optical ocular.

Design of NVDs is apparently easy because crucial modules like image intensifier tube, optical objectives, optical oculars (eyepieces) are available on the market from dozen or more sources. However, in spite of this apparent design simplicity, the process of creating output image by these imaging systems is quite sophisticated. Many design rules must be well understood by manufacturers to deliver

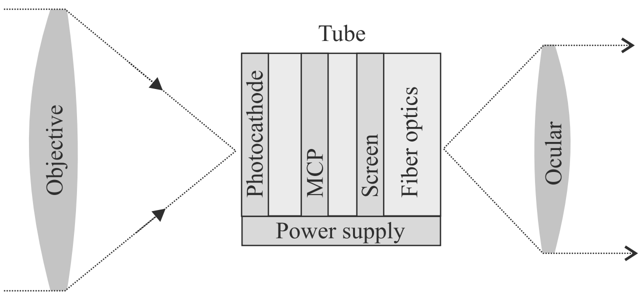


Fig. 1. Block diagram of night vision monocular.

high performance NVDs. Every manufacturer of NVDs must carry out some kind of performance/cost optimization that requires deep knowledge of process of influence of different modules on quality of final image and functionality of final night vision device.

Night vision devices have a relatively long history in comparison to thermal imagers or visible/NIR cameras. First NVDs have been developed before the end of the Second World War [1] in situation when the first thermal imagers have been developed at the beginning of 1970s; and the first visible/NIR cameras based on modern solid state technology appeared on market in 1980s. However, NVDs have received much less attention from international scientific community than thermal imagers or visible/NIR cameras due to two reasons. First, technology of image intensifier tubes (crucial module of NVDs) has been developed mostly by big manufacturers, not by scientific institutes. The manufacturers have a natural unwillingness to free access publications in contrast to scientific institutes. Second, it was predicted many times that night vision technology will demise in near future due to competition from more modern surveillance imagers like thermal imagers, low light visible/NIR cameras (ICCD/EMCCD cameras), or more recently – SWIR imagers. Therefore, night vision technology has been treated by most scientists as rather old, unfashionable technology in the last several decades.

This low interest of scientific community in night vision technology resulted in a small number of specialist literature, a certain chaos in available literature, conflicting claims of superiority of different types of image intensifier tubes, marketing arguments promoted by different manufacturers and repeated by some scientists. Even specialists in night vision technology can have real problems with objective evaluation of modern night vision devices on the basis of available literature data.

This paper presents a review of modern night vision technology with aim to present a logical, consistent vision of this technology divided using a series of criteria. NVDs are classified in dependence on design configuration of NVD, type of image intensifier tube, type of night vision optics, targeted market, type of aviator NVD, and compatibility to aviation regulations. Short review of parameters and development trends of night vision technology are presented, as well.

2. Design configuration

There is no internationally accepted division of NVDs. The same types of NVDs can have different names in different literature sources. Here we will follow a division and a terminology used at websites of two big manufacturers of NVDs and divide modern night vision devices into four basic types [2,3]:

1. Night vision goggles;
2. Night vision monoculars;
3. Night vision sights;
4. Night vision binoculars.

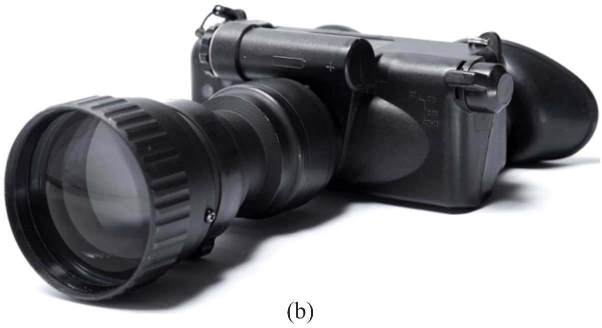
Over 99% of NVDs offered on world market can be treated as equivalents of the models listed above and shown in Figs. 2–5.

Fig. 2. Night vision goggles: (a) binocular night vision goggles type AN/AVS–9 (ITT Night Vision [4]), and (b) monocular night vision goggles type BIG 25 (Vectronix AG [5]).

Fig. 3. Night vision monocular type Tarsius (Vectronix AG [5]).

Fig. 4. Night vision sight type Trident (ATN Corp. [2]).

(a)



(b)

Fig. 5. Night vision binoculars: (a) two-channel ATN Night Raven-2 binoculars (ATN Corp. [2]), and (b) single-channel Diana 3x binoculars (Optix Corp. [6]).

The first two groups of NVDs (goggles, monoculars) are basically devices of a wide field of view (FOV) similar to human vision (FOV about 40°, magnification equal to one). These NVDs can be treated as human eyes of improved sensitivity.

Binocular night vision goggles enable observation using two eyes to achieve stereo vision (three-dimensional (3D) vision). In other words, human using binocular night vision goggles can achieve perception of depth from two slightly different projections of the world onto the retinas of the two eyes. Binocular night vision goggles are typically used by pilots, drivers or other people who need a 3D-vision of surrounding scenery at night conditions.

Monocular night vision goggles can be treated as a cheaper version of the earlier discussed binocular night vision goggles. Two costly image intensifier tubes are replaced by one tube. A comfortable two-eye observation is still possible. Some depth perception is still achieved even during a single-channel observation.

In case of night vision monoculars the simplification process goes even further. The monoculars are practically one-channel binocular night vision goggles. Price is reduced by factor at least two in comparison to binocular night vision goggles. Additional advantage is small size and mass of these devices.

The last two groups of NVDs (sights, binoculars) are basically devices of narrow field of view (FOV from about 4° to about 13°, magnification from about 3 to about 10). These devices can be treated as human eyes of improved sensitivity equipped with magnifying optical scope.

Night vision sights (called also often night vision scopes) are generally monoculars of a narrow FOV that provide magnification of an image perceived by a human operator by a factor from 3 to 10. These devices are typically attachable to weapons.

Night vision binoculars are night vision goggles built by using bigger optical objectives of a longer focal length. The binoculars enable magnification of an image perceived by a human operator by a factor from 3 to 10 like typical day level binoculars. If built using two separate optical channels then the binoculars offer also stereoscopic vision.

So far, we listed four different basic types of NVDs that look and work differently from final user point of view. However, night vision devices can be divided in different way taking into account their design. From the latter point of view differences between goggles and binoculars, and between monoculars and sights are small. The differences are caused only by one module; optical objective. Because of this minor technical difference, the borders between earlier discussed groups of NVDs are fluid. Night vision goggles can be easily converted to night vision binoculars if optical objectives are exchanged for bigger objectives of a longer focal length or some afocal adapters are added. Then, night vision monoculars can be converted into night vision sights by exchanging objective and by adding some mechanics that make possible to attach the monocular to weapons. There are many such NVDs on the market.

Therefore, from designer point of view, NVDs are divided into three basic types (Fig. 6):

1. Bino-channel NVDs;
2. Mixed channel NVD;
3. Mono-channel NVD.

Technical differences are significant between them and it is not possible to convert easily one type of NVDs to another types of NVDs. The latter division is based on more logical ground and presents deeper differences than the earlier discussed commercial division. However, the first division is more popular and should be remembered if someone wants to understand terminology used by manufacturers of NVDs.

So far NVDs have been divided using easily visually noticeable differences (number of objectives, number of oculars, size of objective, field of view). Now, let us discus more subtle, but also more important differences between different NVDs.

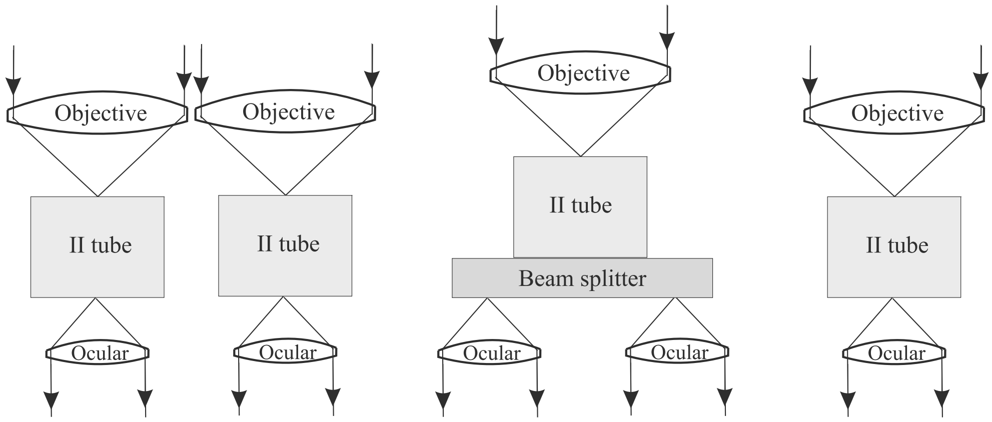


Fig. 6. Block diagrams of three types of night vision devices: (a) bino channel NVDs, (b) mixed-channel NVDs, and (c) mono channel NVDs.

3. Image intensifier tubes

Image intensifier tubes (IITs) are vacuum tubes that amplify a low light-level image to observable levels. The incoming light is converted into photoelectrons through a photocathode of the tube. Next, highly intensified photoelectrons strike the phosphor screen (anode) and a bright image is created that human can easily see.

Image intensifier tubes are the most important component of night vision devices and typical classification of night vision devices is based on a tube classification.

IITs are typically divided into several generations in dependence of the method to amplify incoming light (photocathode material, tube design structure) as the basic criterion. IITs can be also classified by using other criteria like type of input optics, type of output optics, phosphor screen, photocathode size, or tube performance.

Five parameters of IITs must be defined to enable precision discussion about division of these tubes:

1. Radiant sensitivity is a ratio of current induced into a photocathode (in mA units) of tested tubes by incoming light (in Watt units) for a specified wavelength.
2. Luminous sensitivity is a ratio of current induced into a photocathode (in µA units) of the tested tube by flux (in lumen units) of incoming polychromatic light of colour temperature equal to 2856 K.
3. Luminance gain is a ratio of luminance of output image (tube screen) to luminance of input image (tube photocathode). Measurement is done using light source of colour temperature equal to 2856 K. Luminance gain can be presented in several ways: in cd/lx¨·m^2 units (candela per lux times square meter), in lm/lm units (lumen per lumen), or in fL/fc (foot-lambert per foot candela). Image generated by a tube of low luminance gain looks darker than image generated by a tube of high luminance gain at the same input illuminance conditions.
4. Resolution is defined as a spatial frequency of a minimal 3-bar pattern of USAF 1951 target that can be resolved by an observer. Resolution is presented in lp/mm (line pairs per millimeter) units. Simulated images of USAF 1951 target of two tubes of different resolution at input illumination about 3 mlx generated using a Nightmet computer simulator program are shown in Fig. 7 [7]. Nowadays, resolution of typical IITs available on market is about 50–57 lp/mm; resolution of the best tubes can reach level of 81 lp/mm.
5. Signal to noise ratio (SNR) is a ratio of two components of a light signal emitted by a small part of a tube screen: average signal to root mean square signal (noise). The output signal is generated by illuminating a small part of photocathode (diameter 0.2 mm) at typical level of 108 µlx. Simulated images of USAF 1951 target of two tubes of different SNR at input illumination about 0.3 mlx obtained using Nightmet computer simulator program [7] are shown in Fig. 8. Nowadays, SNR of typical IITs available on market is about 18–22; SNR of the best tubes can reach level of 30.

3.1. Generations of image intensifier tubes

First night vision devices were developed during the Second World War [1]. The technology of image intensifier tubes has progressed very significantly since that time. This progress can be described using different divisions but the most

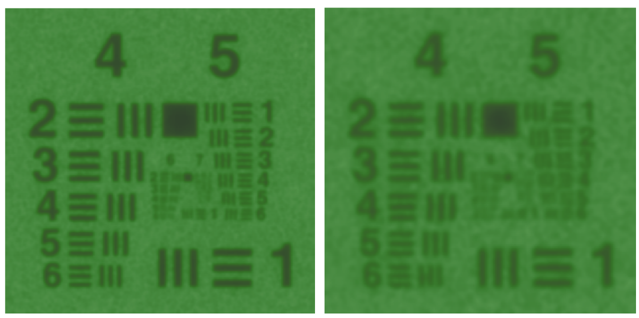
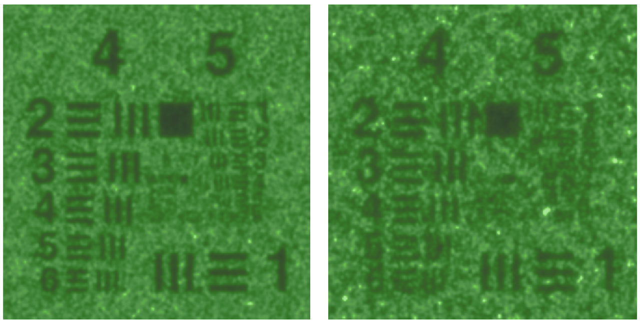


Fig. 7. Magnified image of USAF 1951 resolution target generated by two tubes of different resolution: (a) tube of resolution 64 lp/mm and (b) tube of resolution 40.3 lp/mm (case of high input illumination).



(a) (b)

Fig. 8. Magnified image of USAF 195,1 resolution target generated by two tubes of different SNR: (a) tube of SNR equal to 28 and (b) tube of SNR equal to 18 (case of low input illumination).

popular is division onto generations. US military has dictated the name of the generation of IITs over the last five decades. It should be however remembered that the division on generations is assumed in USA and presents US point of view on the night vision technology.

There are so far four enerations of image intensifier tubes: Gen 0, Gen 1, Gen 2, Gen 3 – at least according to the official US terminology. In general, generation numbering is related to significant changes in design of IITs that improve (with some exceptions) performance of these tubes.

As we see in Fig. 9, different generations of IITs use different photocathodes. There is a big positive difference between S–1 photocathode used by Gen 0 tubes and S–10 photocathode used by Gen 1 tubes. The positive difference between S–25 photocathode used by Gen 2 tubes and S–10 photocathode used by Gen 1 tubes is not so obvious. However, we must take into account that critical parameter of photocathodes of IITs – luminous sensitivity – is measured using light sources of 2856K colour temperature. This measurement method (simulating to some degree real applications) strongly favours photocathodes more sensitive in near infrared range – in this case S–25 photocathode. Finally, GaAs photocathodes used in Gen 3 tubes are again clearly

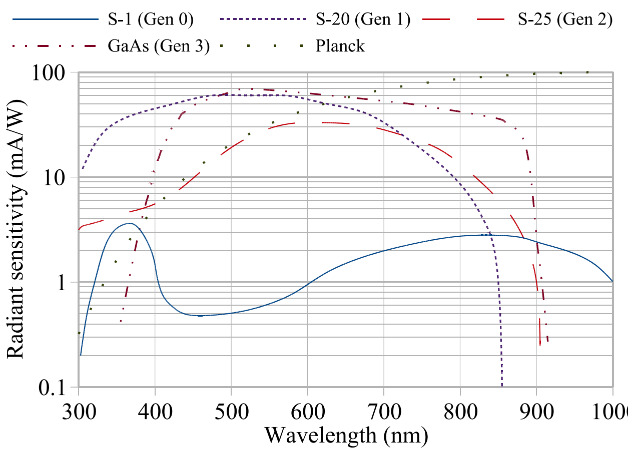


Fig. 9. Spectral sensitivity of typical photocathodes: S1(Gen 0), S–20 (Gen 1), S–25 (Gen 2), GaAs (Gen 3) and relative Planck curve.

more sensitive than S–25 photocathodes used in tubes of previous generation.

It should be noted that radiant sensitivity of photocathodes type S1, S20, S25 and GaAs can vary significantly. The graphs presented in Fig. 9 refer to tubes considered as typical based on practical experience of author.

Differences between different generations of IITs are much deeper that the simple scheme shown in Fig. 9. Several more parameters should be considered in order to show important differences between tubes of different generations. Photocathode material is only one of these parameters. Next, the differences between different generations are not always clear. Further on, some of generations can be further divided into sub-generations. All these subtle details shall be now discussed.

Generation 0 refers to the technology developed during World War II, employing fragile, vacuum-enveloped image converters with poor sensitivity and little gain. These were single stage tubes that achieved image intensification due to acceleration by high voltage of electrons emitted by the photocathode and striking the phosphor screen. S–1 (silver-oxygen-caesium) photocathode, electrostatic inversion and electron acceleration were typically used to increase brightness of input image.

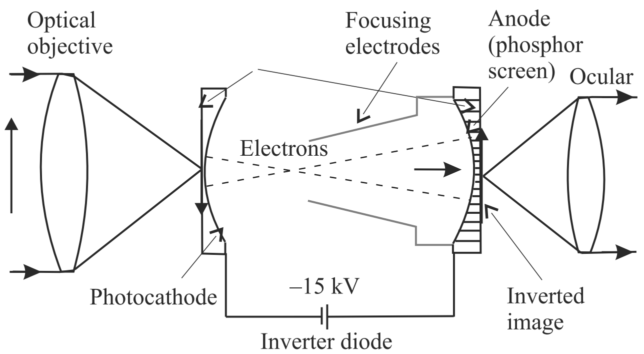
S–1 photocathode has two small peaks of its sensitivity: the first in ultraviolet (UV) and the second in near infrared (NIR) about 800 nm, but is characterized by low sensitivity at visible band (Fig. 9). This situation fits badly for a task to amplify brightness of input image created by nocturnal light characterized by negligible amount of UV light and high amount of visible light. Therefore, luminous sensitivity of S–1 photocathodes was not higher than about 60 μA/lm (microampere per lumen). Further on, luminance gain was no more than about 150 lm/lm. Such a low luminance gain is not sufficient to create a bright image of scene of interest at typical night conditions. Therefore, Gen 0 tubes were in the past used in active night vision systems cooperating with an IR illuminator. High power tungsten bulbs covered with an IR filter suppressing visible radiation were used as illuminators. Active character of use of these first night vision devices was their significant disadvantage.

Generation 1. First Gen 1 tubes were in general improved Gen 0 tubes. Initial experiments with new photocathode materials showed that S–11 photocathode (cesium-antimony) is characterized by an extremely high quantum efficiency up to 20%) but only in a visible range. Therefore, only slight improvement of luminous sensitivity to the level of 80 μA/lm was achieved using this new type of photocathodes because the value of luminous sensitivity depends more on tube sensitivity in near infrared band than on sensitivity in visible band.

The breakthrough came about 1956 with a discovery of S–20 photocathode (multialkali photocathode: sodium-potassium-antimony-cesium) that is sensitive in both visible and near infrared (Fig. 9). Significantly improved photocathode sensitivity (luminous sensitivity up to 200 μA/lm), and improved technique of electrostatic inversion and electron acceleration enabled to achieve luminance gain from about 400 lm/lm to about 800 lm/lm. Because of this quite high luminance gain some of Gen 1 NVDs were used as passive night vision systems, but majority of Gen 1 tubes was still used in active systems. The reason for using support of artificial infrared illuminators is the fact that much higher luminance gain in the order over 30 000 times is necessary to achieve ability to see even at medium illuminated (overcast quoter moon) night conditions.

First generation IITs are characterized by good image resolution (25–30 lp/mm), a wide dynamic range (the ability to reproduce the ratio between bright and dark parts of an image), low noise, and clear image with few blemishes. Due to earlier mentioned advantages and low production costs, Gen 1 tubes are still manufactured and NVDs built using Gen 1 tubes still dominate in commercial market. However, Gen 1 tubes are only very rarely used for military applications due to low luminance gain and significant distortion present in images generated by these tubes.

From technical point of view Gen 1 tubes are apparently simple devices. Focusing is achieved by using an electron lens to focus electrons, originating from the photocathode, onto the screen (Fig. 10). In the inverter diode tube presented in Fig. 10 an electrostatic field directs the photoelectrons and focuses an inverted image on the phosphor screen. Electron lens can be achieved by combining an electrostatical field with an axial magnetic field provided by either a solenoid or permanent magnet. A uniform magnetic field enables to achieve a good resolution over the entire screen and at the same time keeps distortion low. Fibre optics windows are used in Gen 1+ tubes to minimize degradation of the image resolution towards the edge of the tube. The fibre optics can potentially enable also efficient coupling to another image tube, to an imaging detector, or to photographic film.



(a)

(b)

Fig. 10. Gen 1 tube: (a) diagram of a NVD built using a Gen1 tube, and (b) photo of Gen 1 tube with external electronic power supply.

As it was earlier said, luminance gain of a single Gen 1 tube was still too low to enable design a truly passive NVDs. A simple solution to overcome this drawback was proposed in a form of a cascade tube built by combining two or three single tubes. The experiment carried out in 1950s showed that it is possible to design a cascade tube of luminance gain even over the level of 30 000 lm/lm capable to produce a usable image of scenery of interest even at starlight conditions. The first cascade tubes coupled using optical systems were too bulky (length up to about 40 cm) to be used in NVDs for military applications. However, introduction of fibre optics for coupling of image intensifier tubes enabled designing of much shorter cascade tubes that were used in big numbers in devices manufactured during Vietnam war in 1960s and partially also during 1970s.

Two other big drawbacks of the cascade tubes were low SNR and high cost of manufacturing. The first drawback means that output images were very noisy because the next stage of the tube amplified noise present in the image generated by the previous stage. The second drawback was caused by the necessity to use typically three single stage tubes to design a single cascade tube. Because of these three earlier discussed drawbacks the cascade tubes were quickly eliminated with advent of Gen 2 tubes in 1970s. Nowadays the cascade tubes are only rarely used in scientific applications.

Generation 2 image intensifier tubes represent a significant breakthrough in night vision technology. These are small, compact IITs that offered luminance gain at the level of about 30 000 lm/lm and the later even more. Such a significant increase of tube luminance gain, while making tube also smaller, was achieved due to four basic reasons.

First, Gen 2 tubes use microchannel plate (MCP) to amplify electrons emitted from photocathode (Fig. 11). The MCP is a very thin plate of conductive glass containing millions of small holes. An electron entering a channel strikes the wall and creates additional electrons, which in turn create more electrons (secondary electrons), again and again (Fig. 11). The microchannel plate is an array of miniature electron multipliers oriented parallel to one another and have length to diameter ratios between 40 and 100. Channel axes are typically normal to, or biased at a small angle (≈ 8°) to the MCP input surface. The channel matrix is usually fab-

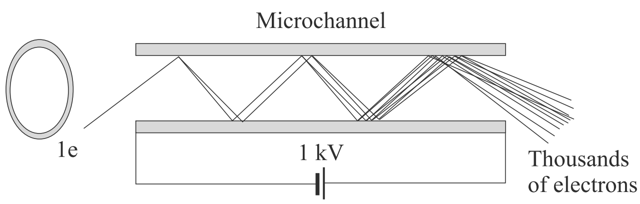


Fig. 11. Principle of work of a microchannel plate.

ricated from a lead glass, treated in such a way as to optimize the secondary emission characteristic of each microchannel and to render the channel walls semiconducting, so as to allow charge replenishment from an external voltage source. Parallel electrical contact to each channel is provided by the deposition of a metallic coating on the front and rear surfaces of the MCP, which then serve as input and output electrodes, respectively. The total resistance between electrodes is in the order of $10^9\ \Omega$. Such microchannel plates allow electron multiplication factors of 10^3–10^5 depending on channel length and number of layers. Spatial resolution is limited by channel dimensions and spacing; 12 μm diameter channels with 15 mm center-to-center spacings was typical for first and second generation tubes. Nowadays both dimensions and spacing can be about two times smaller.

Second, Gen 2 tubes use new S–25 photocathode. This is actually the same multialkali photocathode as S–20 photocathode used in Gen 1 tubes but S–25 photocathode is built using thicker layers of the same materials. In this way extended red response and reduced blue response was achieved making sensitivity spectrum of S–25 photocathode well matched to spectrum of nocturnal light. Luminous sensitivity of the first S–25 photocathodes was about 250 μA/lm. It is a noticeable improvement in comparison to S–20 photocathode used in Gen 1 tubes but almost negligible in comparison to revolution in luminance gain achieved by introduction of MCP plate.

Third, first Gen 2 tubes were inverter tubes that used an electrostatic inversion, in the same way as the Gen 1 tubes did, but with an added MCP (Fig. 12). The size of Gen 2 inverter tubes was only slightly lower than size of Gen 1 tubes. However, introduction of proximity focused tubes that could also carry out an image inversion using a fibre bundle with a 180 degree twist in it enabled the design of much smaller tubes (Fig. 13). Nowadays, almost all tubes used for night vision applications are proximity focused tubes.

Fourth, Gen 2 tubes were integrated with small electronic modules capable not only to power tubes using high voltage but also to carry out automatic gain control and bright spot protection. This new feature is a sharp contrast to a bulky external high voltage power supplies used by Gen 1 tubes (Fig. 10).

To summarize, Gen 2 tubes should be treated as a real revolution in image intensification technology. There is a big difference between Gen 2 tubes and Gen 1 tubes in situation when border between Gen 3 tubes and Gen 2 tubes is much more blurred, especially between Gen2+ tubes and Gen 3 tubes.

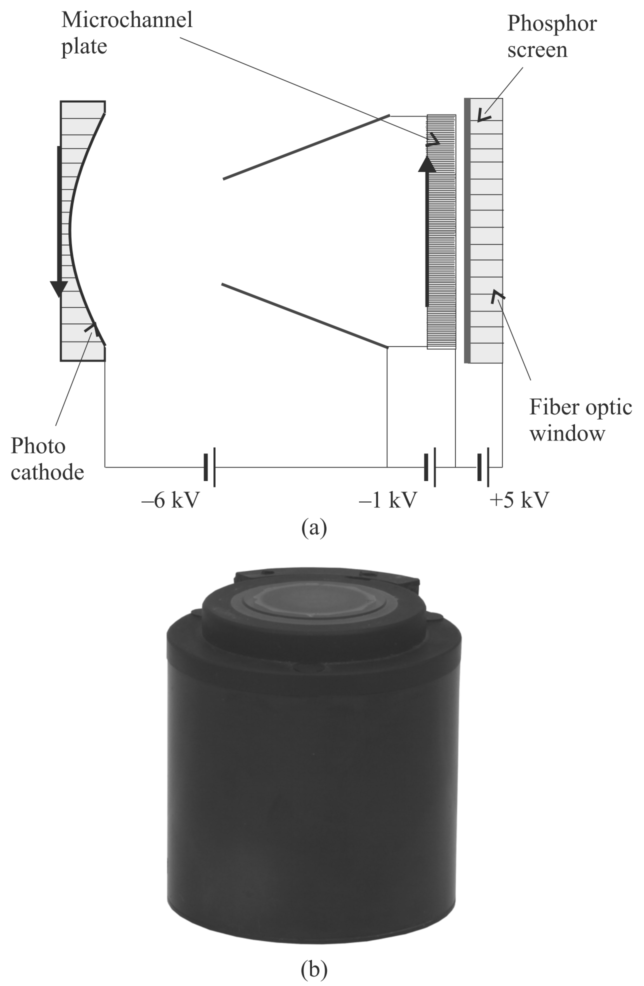


Fig. 12. Inverter Gen 2 tube: (a) diagram and (b) photo (tube dimensions Φ52.8×55.5 mm).

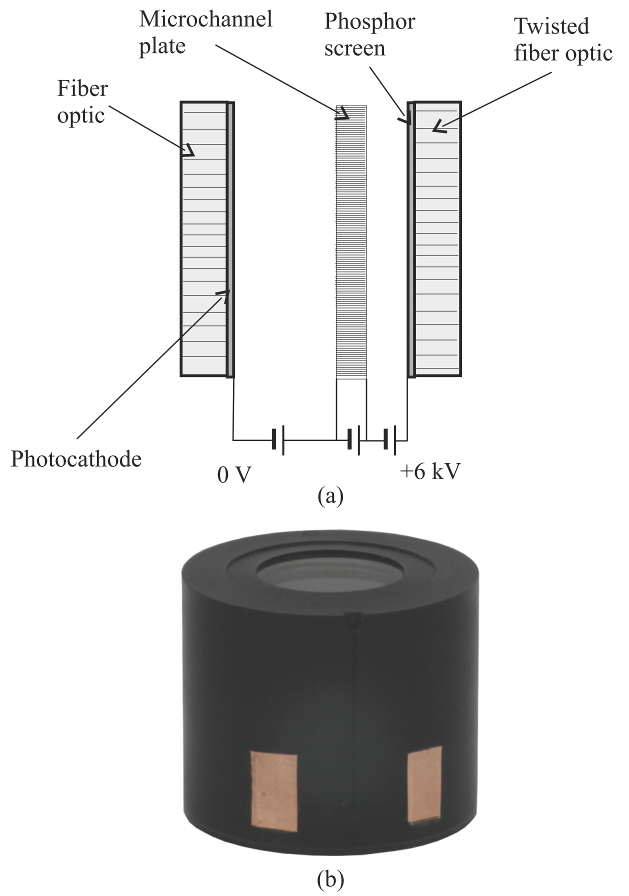


Fig. 13. Proximity focused Gen 2 tube: (a) tube diagram and (b) photo (tube size Φ35.5×31 mm).

Two plus generation (Gen 2+) is not formally recognized by U.S. authorities. This term refers to technologies used to improve sensitivity of the tri-alkali S–25 photocathodes and manufacturing new generation microchannel plates. In detail, photocathode sensitivity was improved more than two times, microchannel plates of highly increased open-area ration up to about 70%, and reduced internal noise were developed. These new technologies enabled to manufacture Gen 2+ tubes of expanded spectral sensitivity up to about 950 nm and of luminous sensitivity up to about 700 μA/lm. First Gen 2+ tubes were developed by Photonis company (France) in 1989. Further development of Gen 2+ tubes has been continued by several non-U.S. manufacturers in France, Netherlands, Russia, China, and India. Nowadays Gen 2+ tubes (marketed using different names like Gen II Plus, SuperGen, HyperGen, XD4, XR5) represent majority of hi-end image intensifier tubes manufactured by non-U.S. manufacturers.

Gen 3 tubes are very similar to the Gen 2 tubes from design point of view. The primary difference is the material used for the photocathodes. The second generation image intensifiers use photocathodes with a multialkali coating whereas the third generation image intensifiers uses photocatodes with a GaAs/GaAsP coating. The latter photocathodes are characterized by higher sensitivity and additionally the spectral sensitivity band is extended more in near infrared (Fig. 9).

Manufacturing of Gen 3 tubes was started in 1980s but some development works were done earlier in 1970s. Literature sources state that the photocathodes used in Gen 3 tubes are characterized by radiant sensitivity in the near infrared about three times better in comparison to photocathodes with a multialkali coating used by Gen 2 tubes (Fig. 14) [8].

Higher radiant sensitivity of Gen 3 tubes means higher luminous sensitivity. SNR is theoretically proportional to square root from luminous sensitivity. Therefore, the situation shown in Fig. 14 should theoretically guarantee SNR of Gen 3 tubes to be about two times better than for Gen 2 tubes. However, such a conclusion is typically not true due to two main reasons. First, radiant sensitivity of modern Gen 2+ tubes is much better than data shown in Fig. 14. Second, Gen 3 photocathodes have a significant drawback. These photocathodes can be quickly seriously degraded by positive ion poising that can reduce photocathode sensitivity up to about two times within a period about 100 hours. In order to protect the photocathode from positive ions and gases produced by the MCP, manufacturers of Gen 3 tubes have added a thin film of sintered aluminium oxide attached to entrance of the microchannel plate. This technique protects effectively photocathode but the protecting film traps about half of electrons emitted by the photocathode. These trapped electrons will not be amplified. Therefore, the effective luminous sensitivity of Gen 3 tube can be almost two times lower than photocathode luminous sensitivity of such a tube. The final result is that SNR of typical Gen 3 tubes is often comparable to good Gen 2+ tubes. The diagram presented in Fig. 15 explains graphically the earlier mentioned effect of reduction of effective sensitivity of Gen 3 tubes.

The protecting film generates also significant blurring that occurs when it is bombarded by a high intensity concentrated electron beam. Therefore, halo effect in Gen 3 tubes is typically significantly bigger than in Gen 2+ tubes (Fig. 16).

In 1998 the U.S. company Litton informed general public about the development of the filmless image intensifier tube built using the GaAs/GaAsP photocathodes [10]. Development of such tubes meant elimination of main drawback of Gen 3 tubes – the ion protecting film trapping electrons emitted by photocathode (Fig. 17). This new technological solution could potentially increase SNR of IITs at least over 25%. Therefore, the new tubes caused significant

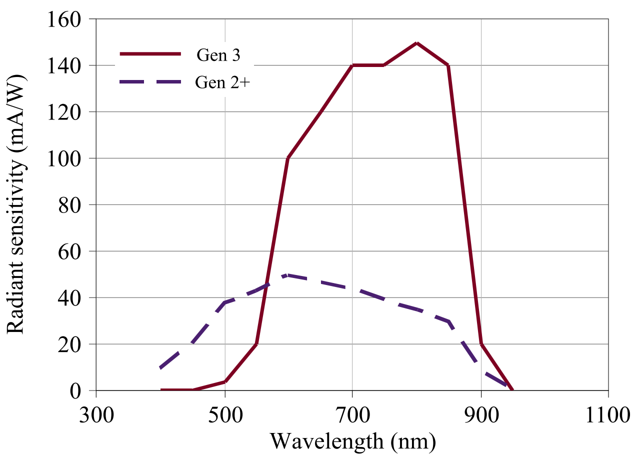


Fig. 14. Radiant sensitivity curves of Gen 2 tube photocathode (S–25 extended red multialcali) and Gen 3 tube (GaAs) photocathode (after Ref. 8).

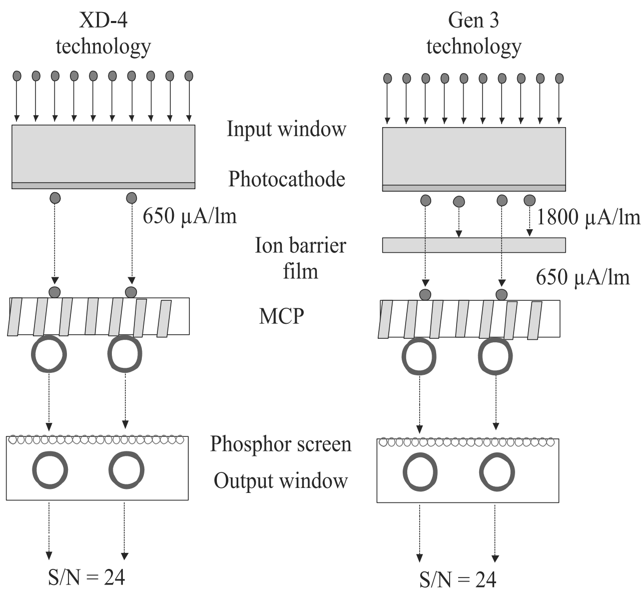


Fig. 15. Two tubes (Gen 2+ tube – XD–4 class and Gen 3 tube) of much different luminous sensitivity generating output image of the same signal to noise ratio (after Ref. 13).

Fig. 16. Image generated by two night vision devices built using image intensifier tubes of different halo: (a) big halo, and (b) small halo (after Ref. 9).

interest of U.S. military authorities and Night Vision and Electronic Sensors Directorate (NVESD) assigned these new tubes as Gen 4 tubes. However, it was soon found that the new Gen 4 tubes are too fragile for real military conditions (sensitivity to mechanical shock) and additionally cannot pass typical reliability tests when the tubes are exposed to sudden uniform/concentrated flashes of light. Therefore, in 2002 NVESD revoked its previous decision designating filmless tubes as Gen 4 tubes. Since that time these new tubes are called as Gen 3 Filmless tubes and there is officially no Gen 4 tubes.

Despite of setback with reliability problems development of Gen 3 filmless tubes have been continued and brought significant technology improvements. Two techniques have been found to overcome the problem of photocathode poisoning. First, using of improved scrubbing techniques during manufacture of the microchannel plate that is the primary source of positive ions in a wafer tube. Second, using of autogating technique to power photocathode because a sufficient period of autogating causes positive ions to be ejected from the photocathode before they could cause poisoning of the photocathode [10].

Gen 3 Filmless tubes are characterized by excellent SNR (can be even over 30) and can produce clear image of scenery of interest even under very dark, moonless nights. Therefore, Gen 3 Filmless tubes are often used in night vision goggles for aviators or for special operation teams, but are avoided in night vision sights due to their vulnerability to mechanical shock.

Gen 3 Filmless tubes represent one group of significantly improved Gen 3 tubes. Gen 3 Thin Film tubes represent another group of improved Gen 3 tubes, and are often called Gen 3+ tubes.

Gen 3 Thin Film technology was developed by ITT Night Vision (the biggest U.S. manufacturer) as a response to competition from Gen 3 Filmless tubes offered by another U.S. manufacturer – Litton. ITT Night Vision found that by significantly thinning, rather than removing the protective film, it could achieve the army-mandated Gen 4 performance and end-of-life reliability requirements [12]. Maintaining the film also would protect all the important gallium arsenide photocathode structure. Therefore, Gen 3 Thin Film tubes use ion protecting ultrathin film of the thickness about 3 nm (typical situation) or sometimes as thin as 1 nm. Reduced voltage applied to photocathode is another but minor change in comparison to typical Gen 3 tubes.

Thin Film technology is not as effective as filmless technology in eliminating trapping of electrons emitted by photocathode. Up to 25% of electrons are still trapped by the

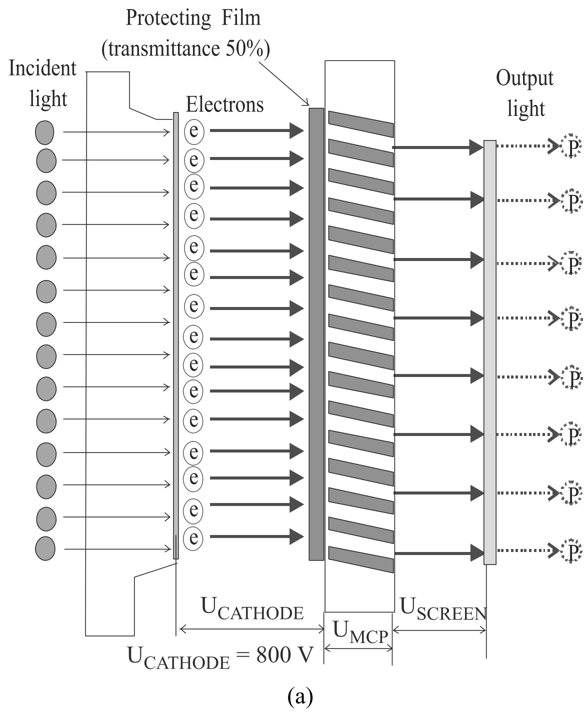


Fig. 17. Graphical presentation of difference between Gen 3 tubes and Gen 4 tubes: (a) typical Gen 3 tubes, and (b) filmless Gen 4 tube (after Ref. 11).

thin protecting film. However, these losses are much lower than in case of typical Gen 3 tubes and Gen 3 Thin Film tubes offer very good SNR; almost as high as for Gen 3 Filmless tubes. At the same time Gen 3 Thin Film tubes are characterized by better reliability than Gen 3 Filmless tubes. Therefore, Gen 3 Thin Film tubes are nowadays the main group of hi-end image intensifier tubes used by U.S. military.

Short summary of basic features of different generations of IITs is shown in Table 1. It is clear that the generation number is a code that gives general description about technology that is used to manufacture the tubes. There are sub-classes within each of main generations depending on technology details.

The presented earlier division of image intensifier tubes into several generations is based on a manufacturing technology as the main criterion. As it was mentioned earlier there is no clear precision relationship between generation number and tube performance.

Gen 3 Filmless tubes and Gen 3 Thin Film tubes are two technologies that significantly improved performance of image intensifier tubes within last decade. Gating is the third less noticeable technology that improved performance of modern tubes.

Gating means a technique used to switch on and off image intensifier tube like an electronic gate. For several decades this technique has been used in gated image intensifiers used in high speed imaging systems to enable visualization of ultra fast temporal events (time intervals in nanoseconds or even picoseconds). More recently gated tubes have found application in active night vision systems that can potentially enable visualization of targets behind semi--transparent obstacles (including fog) and to measure distance to the target. However, both high speed gated night vision systems and active gated night vision systems are rather exotic types of night vision systems that are used rather rarely.

Auto-gating is a type of gating technique that has found mass application in modern image intensifier tubes. The experiments with this technique were carried out for a decade or more, but autogated tubes appeared on market about 2006 year. These tubes gate voltage applied to photocathode and MCP in order to keep constant current flowing through the MCP even when tube is strongly illuminated. The gating is done at very high frequency and is not noticeable on output image. Autogated tubes can be operated at much brighter conditions than typical tubes without damaging tubes or blurring output image. In other words, the autogated tubes are characterized by ultra extended dynamic that the tubes can generate clear image in both dark nights and twilight (or even day time) conditions.

In detail, resolution of typical tubes can drop several times when tube operates at day level illumination (from about 60 lp/mm to about 10–20 lp/mm). Resolution of autogated tubes drops at the same conditions no more than at about 20% (from about 60 lp/mm to about 50 lp/mm). Therefore, this new feature is of high value in military/security applications where illumination conditions can change very rapidly within several seconds and users of NVDs built using non-autogated tubes are blinded by sudden flashes of light or get blurred image at day conditions. At present, autogated tubes becomes increasingly popular in hi-end tubes for military applications. However, it should be noted that auto-gating technique can be used in both Gen 2+ tubes and Gen 3 tubes and the term “autogating” has no direct connection with a particular generation of image intensifier tubes.

3.2. Tube performance

There is a common view that higher generation number means a better tube. It is true if we compare Gen 0, Gen 1 or Gen 2 tubes but do not have to be true if we compare Gen 2 and Gen 3.

Main EU manufacturer of image intensifier tubes, Photonis, claims that generation numbering based on manufacturing technology introduced by U.S. laboratories cooperating with U.S. industry is misleading [13]. Therefore, Pho-

Table 1. Basic parameters of IITs from different generations.

Gen No.	Photocathode material	Photocathode sensitivity [μA/lm]	Design type	Luminance gain [lm/lm]	Resolution [lp/mm]	SNR
0	S1	< 60	inverter tube	< 200	20–60	–
1	S20	< 160	inverter tube	< 800	20–60	–
1+	S20	< 160	cascade inverter tube	< 20 000	20–30	5–8
2	S25	< 350	inverter MCP tube	< 50 000	24–43	12–17
2+	improved S25	< 700	proximity focus MCP tube	< 70 000	43–81	15–24
3	GaAs/GaAsP	< 1600	proximity focus MCP, tube with protecting film	< 70 00	36–64	18–25
3+ Thin Film	GaAs/GaAsP	< 1800	proximity focus MCP, thin film tubes	< 70 000	57–71	24–28
3 Film less	GaAs/GaAsP	< 2200	proximity focus MCP, filmless tubes	< 80 000	57–71	24–31

tonis (formerly also DEP) introduced its own generation numbering. The tubes are divided into four generations:

1. Gen II Plus®;
2. SuperGen®;
3. XD4®;
4. XR5®.

This division is based on tube performance characterized by two important parameters: resolution and SNR, or on the product of these two parameters called figure of merit (FOM). Typical values of resolution, SNR and FOM parameters used by Photonis to characterize mentioned above generations of image intensifier tubes are shown in Table 2 [13].

Table 2. Division of image intensifier tubes proposed by Photonis.

Generation code	Resolution [lp/mm]	SNR	FOM
Gen II Plus®	36	13	468
SuperGen®	51	21	1071
XD4®	64	23	1472
XR5®	72	28	2016

*Values of resolution and SNR are typical values from data sheets at Ref. 13.

The division of image intensifier tubes into several performance generations presented in Table 2 should be treated as a division used locally by only one of main manufacturers. However, the general concept to classify tubes into separate groups on the basis of values of two important parameters like resolution and SNR is quite popular.

U.S. Department of State guidelines for export of image intensifier tubes are nowadays based on FOM values. It is highly probable that the European Community (EU) authorities will follow this example and the old guidelines based mostly on photocathode luminous sensitivity will be revoked. A big advantage of FOM criterion is the fact that the FOM parameter of typical potted tubes can be measured without any damage to the tube in situation when measurement of luminous sensitivity is destructible to potted tubes.

Next, U.S. authorities generated division of image intensifier tubes into generation based on manufacturing technology as the main criterion. According to typical logic tubes of higher generation should be better than tubes of lower generation. Therefore, this official division discussed in Section has been used by U.S. manufacturers to promote U.S. made Gen 3 tubes against Gen 2+ tubes made almost exclusively by non-U.S. manufacturers. However, as it was shown earlier there is no clear precision relationship between generation number and tube performance. Therefore, even in USA, requirements for big purchase programs (coded Omnibus) carried out cyclically by US military have been based mostly not on manufacturing parameters but on performance parameters like resolution and SNR. Therefore, tubes manufactured by U.S. manufacturers are often divided into generations using requirements of Omnibus programs (up to Omnibus VII). Technical requirements on MX 10160 image intensifier tube purchased within Omnibus programs are presented in Table 3 [14]. As we see in this table performance of tubes of the same MX 10160 family purchased within different Omnibus program differ very significantly.

It was reported recently that contracts within new Omnibus program (OMNI VIII) were awarded [15]. However, technical details of OMNI VIII are not known and will not be discussed here.

To summarize, tube performance is not directly related to generation number. Situation when Gen 2+ tubes is better than Gen 3, or even to a lesser degree better than Gen 3+ is possible but inverse situation is equally probable. All tube manufacturers claim advantages of their tubes but often forget about drawbacks.

There are three technologies that are competing in market of hi-end tubes for ultra demanding military applications: improved Gen 2+ tubes (XR5 type or equivalents),

Table 3. Requirements on MX 10160 type image intensifier tube in Omnibus programs.

Contract	Omni I	Omni II	Omni III	Omni IV	Omni V	Omni VI	Omni VII
Resolution lp/mm	36	45	51	64	64	64	64
S/N	16.2	16.2	19	21	21	25	28
FOM	583	729	969	1344	1344	1600	1792
Photocathode sensitivity µA/lm@2856 K	1000	1000	1350	1800	1800	2000	2200
Gain [fL/fc]	20000–35000	40000–70000	40000–70000	40000–70000	40000–70000	50000–80000	50000–80000
MTF@2.5 lp/mm	0.83	0.83	0.9	0.92	0.92	0.92	0.92
MTF@7.5 lp/mm	0.58	0.6	0.7	0.8	0.8	0.8	0.8
MTF@15 lp/mm	0.28	0.38	0.45	0.61	0.61	0.61	0.61
MTF@25 lp/mm	0.08	0.18	0.2	0.38	0.38	0.38	0.38
Halo (mm)	1.47	1.47	1.47	1.25	1.25	0.90	0.70
Phosphor	P–20	P–20	P–20/P–43	P–43	P–43	P–43	P–43
Year	1982	1985	1990	1996	1999	2002	2006